QUANTITATIVE ANALYSIS OF CROSS-COUNTRY FLIGHT PERFORMANCE DATA

A Thesis

Presented in Partial fulfillment of the Requirements for

Graduating with Distinction from the

College of Engineering of The Ohio State University

By

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ABSTRACT

The aviation industry depends heavily on the trained professionals that control the aircraft from the cockpit. Airlines invest substantial resources to training and evaluating these pilots. Today, most of those assessments of pilot performance are based on subjective evaluations by another experienced pilot called a check airman. In order to better train and evaluate pilots' performance, quantitative methods of evaluation are required. Through the use of a flight data recorder (FDR), the various parameters of a flight segment were analyzed, including ground track and altitude. By developing a set of metrics to quantitatively evaluate the performance of a flight, a scale can be established to determine the quality of flight. By combining and modifying the metrics, any phase of flight or set of maneuvers may be evaluated in the future.

For this research project, a FDR was placed in the cargo area of various Cessna 172 aircraft and flown to known locations. The pilots were students of The Ohio State University enrolled in flight education. The data from the FDR was used to analyze the altitude and ground track of the aircraft during the flight. Based on this data, measures were devised to evaluate student performance on future flights. This system will be extremely useful in evaluating solo cross-country flights, where the student is the sole occupant of the aircraft. Students are required by federal regulation to successfully complete several hours of solo flight before obtaining various pilot certificates, and the FDR is a tool that can be implemented to evaluate the performance of the students while they are flying solo.

The purpose of this project was to demonstrate the use of a FDR as a tool of instruction, establish measures for ground track and altitude performance, and to enable an evaluator to predict the chance of a pilot exceeding Practical Test Standards (PTS) minima in straight and level, un-accelerated flight. The project accomplished these goals, and laid the ground work for future research to turn the FDR into a tool for flight instruction, accident investigation, collision avoidance, and pilot performance evaluation.

Dedicated to Nicola Fulks, my future wife.

Thank you for all of your encouragement, patience, and love!

ACKNOWLEDGEMENTS

I wish to thank my adviser, Dr. Jerry Chubb, for all of his advice, assistance, and patience. Without him this project would not have been possible. He provided a room in the Aero Research Laboratory, the flight data recorder, post flight processing software, a computer, and all his knowledge and expertise in writing proposals, technical papers, and theses. He was instrumental in securing a research scholarship for me, and I want to thank him for being not only an advisor and mentor, but also a friend.

I thank Mr. Chuck Ventola and Dr. Urban Lynch for their technical assistance and recommendations in the lab and at the airport.

I am grateful to Mr. Ken Henderson and Mr. David Scarlett for their assistance in acquiring software and hardware.

I also thank all of the pilots and flight instructors who flew the flight data recorder in the back of their aircraft.

I am also grateful to Dr. Larry Kirkbride, Director of Flight Education, for granting permission to me to place the flight data recorder in the back of the flight school's aircraft.

A special thanks goes out to Mr. Gary Fulks who generously lent me his laptop, which proved invaluable in the analysis of the data.

And finally, thank you to The Ohio State University, College of Engineering for the research scholarship that made this project possible.

VITA

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CHAPTER 1

INTRODUCTION

Human factors are identified broadly as contributing to most aircraft accidents (Hobbs, 335). According to Boeing, 62% of all commercial airline accidents are caused in whole or in part by the flight crew, as can be seen in Figure 1.1 (Boeing, 17).

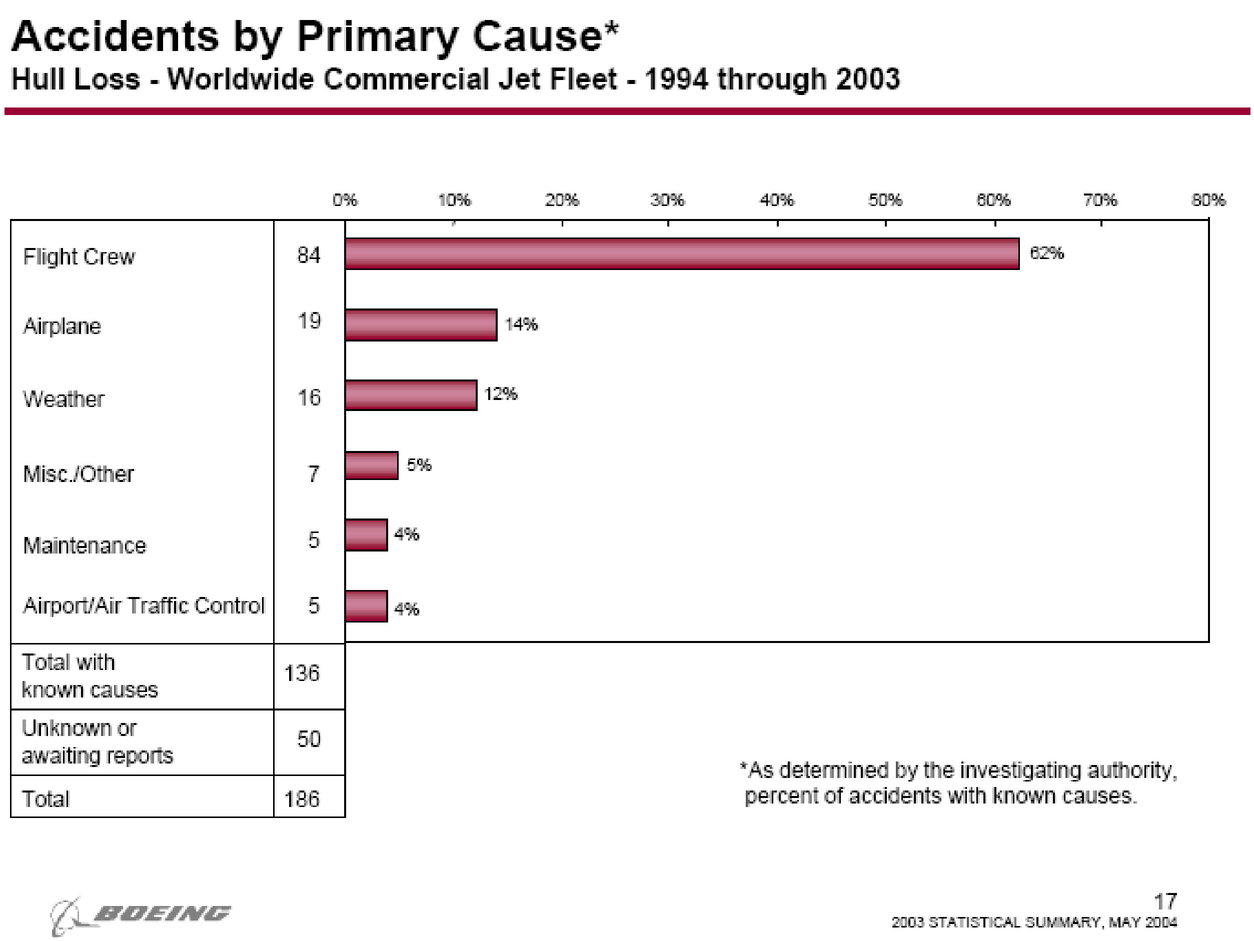


Figure 1.1

To improve aviation safety, highly trained professionals must be available to operate the sophisticated aircraft systems to high performance standards. Pilots are subjected to rigorous testing and evaluation, which today is highly subjective in nature. If a quantitative scale can be developed, all pilots can be held to the same standards, and overall safety should be increased.

Currently, during initial certification, pilots are evaluated by any one of several kinds of examiners: an airline check airman, FAA Inspector, or a Designated Examiner (DE). In all cases, the pilot must perform to criteria specified in FAA Practical Test Standards (PTS) for the particular certificate or rating sought. Each examiner uses his or her discretion and the PTS as a set of guidelines to evaluate the pilot candidate.

The goal of this project was to determine if a quantitative method of evaluating the performance of a pilot executing a specified flying task could be developed. To do this, the most basic of all flight maneuvers was analyzed: straight and level, un-accelerated flight. This type of analysis can be of immediate use to flight instructors trying to evaluate solo cross-country flight performance of their students. At The Ohio State University Flight Education Division, many Aviation Flight Laboratory courses require solo flight lessons, which are not gradable because the student is all alone in the aircraft. The results of this project can be used to remedy this problem, allowing instructors to evaluate their student's performance while flying solo.

To accomplish this goal, a flight data recorder (FDR) was utilized to record the movement of the aircraft about its three axes. An existing ground based software package was used to analyze the 1 Hz GPS data and derive 10 Hz state information based on the known dynamic response of a Cessna 172 airplane. This derived airplane state data was then used to develop a set of metrics to evaluate the overall performance from an objective perspective. Variables such as altitude, azimuth tracking, and deviation were considered. Having now successfully developed these metrics, modifications and enhancements may be made to permit the evaluation of complex maneuvers and cockpit procedures, transforming the training and testing environments of the aviation community in the future. This project's analysis of cross-country flight is only the first step in creating a complete set of metrics to evaluate a pilot's performance over the course of an entire flight.

CHAPTER 2

RESEARCH EQUIPMENT AND METHOD

2.1 Flight Data Recorder

For this project, a Cambridge 401 Flight Recorder was used. This FDR was designed by Cambridge Aero Instruments, Inc. and complied with Fédération Aéronautique Internationale guidelines. It combined a GPS receiver, calibrated sensors, and a non-volatile memory in a single black box that could be inserted in a standard 2.25-inch (57 mm) opening in an aircraft instrument panel. See Figure 2.1 and Figure 2.2. The flash memory could store approximately 50,000 data samples. At the standard rate of 1 Hz, that equates to more than 14 hours of flight time (Cambridge, 1, 7).

Figure 2.1 – Front of the FDR

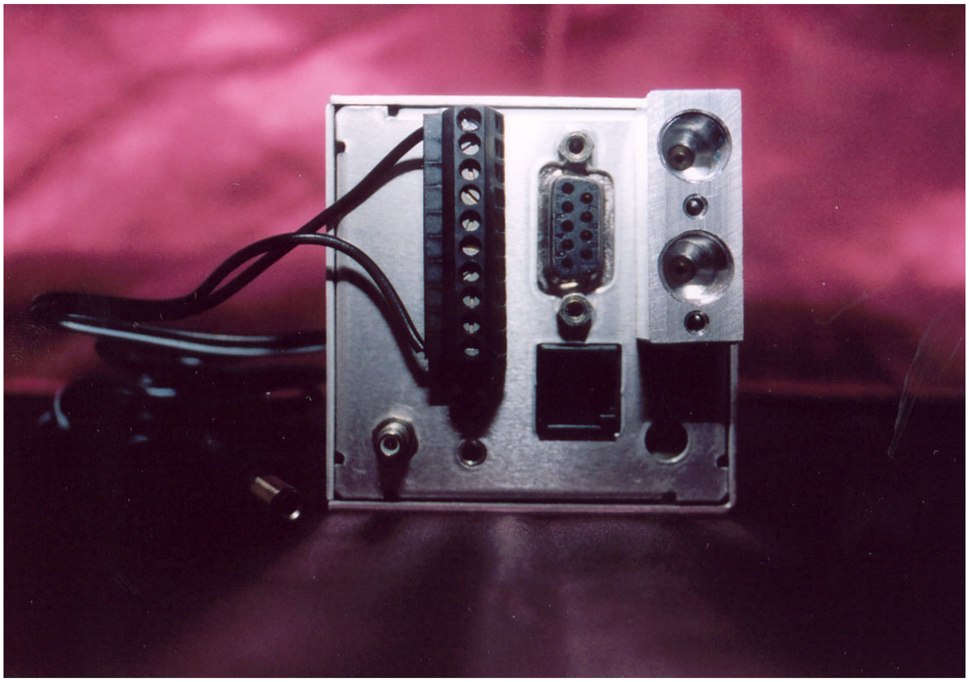


Figure 2.2 – Back of the FDR

The FDR was not installed in an aircraft instrument panel, but was rather attached to a wooden apparatus that could be installed in the back seat of an aircraft by using the seat belt to secure it (Figures 2.4 and 2.5). The apparatus was custom designed and constructed by the author. In addition to holding the FDR, it also held the GPS antenna and the power source, which was a 12-volt, 2.0 ampere-hour, lead-acid, rechargeable battery (Figure 2.3).

Figure 2.3 – Battery

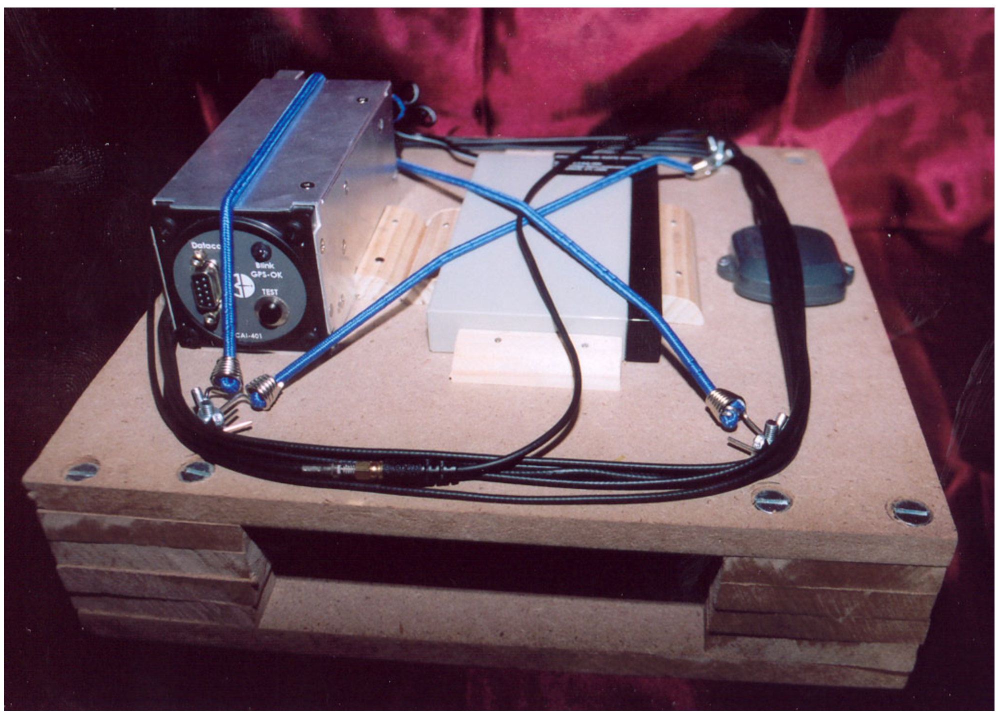


Figure 2.4 – Front of the Assembled Apparatus

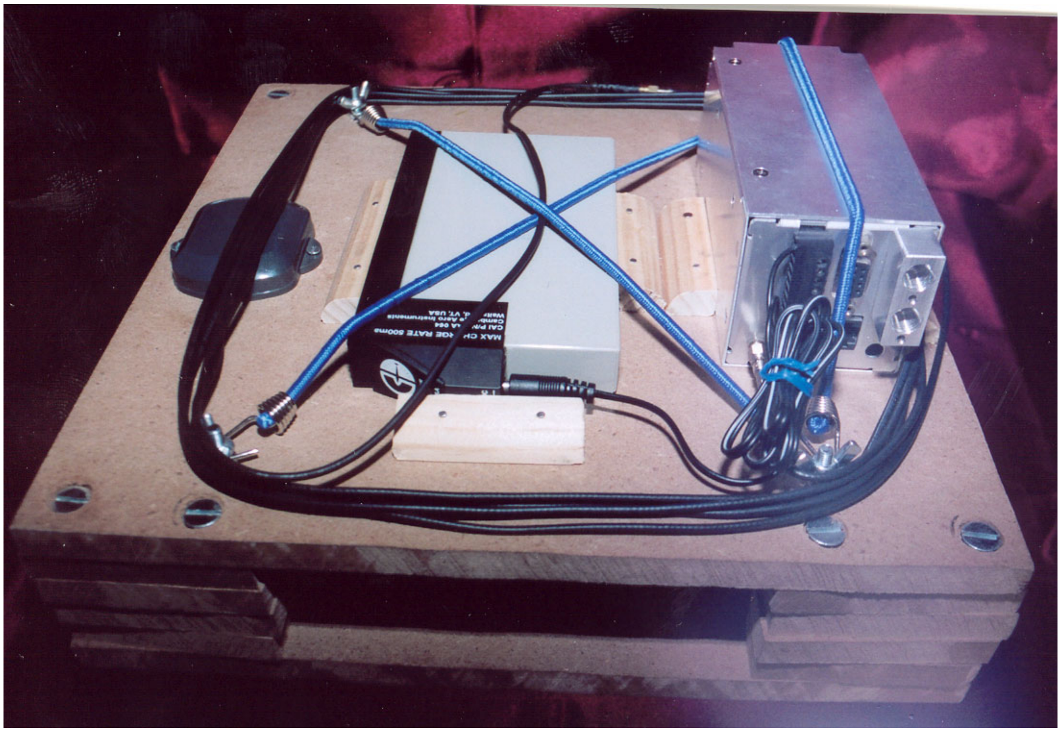


Figure 2.5 – Back of the Assembled Apparatus

The FDR required no intervention of the flight crew to start or stop recording, and the memory card is not erasable. Recording begins automatically when the groundspeed exceeds 10 knots (nautical miles per hour) and records for 2 minutes after the groundspeed has again fallen below that level. One GPS fix is recorded for each second of the flight, and is stored in a flight log for that specific flight. The parameters that are recorded are listed in Table 2.1.

Table 2.1: FDR Data Columns		
Variable	*Units*	*Description*
TIME	Seconds	From beginning of flight
LONG	Degrees	Longitude of aircraft
LAT	Degrees	Latitude of aircraft
XPR	Kft	North position from TIME=0
YPR	Kft	East position from TIME=0
ZPR	Kft	Down position from TIME=0
XPS	Kft	North position from TIME=0
YPS	Kft	East position from TIME=0
ZPS	Kft	Down position from TIME=0
CLIMB	Kft/min	Climb rate
XD	ft/sec	Velocity in X-North Direction
YD	ft/sec	Velocity in Y-East Direction
ZD	ft/sec	Velocity in Z-Down Direction
XDD	ft/sec2	Acceleration in X-North Direction
YDD	ft/sec2	Acceleration in Y-East Direction
ZDD	ft/sec2	Acceleration in Z-Down Direction
V	ft/sec	True airspeed based on GPS position and winds input
MACH	Mach #	Based on V
TAS0	kts	V in knots
VCAS0	kts	Indicated airspeed based on TAS0 at altitude
TASP	kts	True airspeed based on pitot tube measurement
VCASP	kts	Indicated airspeed based on TASP
HEAD	Degrees	Magnetic heading of flight
ELE	Degrees	Elevation angle of velocity vector
AX2	ft/sec2	Wind X-Axis trajectory acceleration
AY2	ft/sec2	Wind Y-Axis trajectory acceleration
AZ2	ft/sec2	Wind Z-Axis trajectory acceleration
AS	ft/sec2	Acceleration in canopy-up direction felt by pilot
ALOAD	Gs	Load Factor
TURNR	deg/sec	Velocity vector turn
BANK	Degrees	Bank angle
PITCH	Degrees	Body pitch angle
YAW	Degrees	Body yaw angle
ROLL	Degrees	Body roll angle
ENGN		Cockpit noise level

NSV		Number of GPS satellites received
IFLAG		GPS drop-out flag (1-no, 0-yes)
TGT1		Adversary-1 aircraft
RNG1	nm	Range to Adversary-1
TGT2		Adversary-2 aircraft
RNG2	nm	Range to Adversary-2
AUAX	Gs	Average longitudinal acceleration
AXMX	Gs	Max longitudinal acceleration
AUAY	Gs	Average up acceleration
AYMX	Gs	Max up acceleration

The flight logs can then be transferred to a personal computer or laptop through the use of a serial cable connected to one of the computer's COM ports. The Utility software program that is included with the FDR is necessary to make this transfer. Through this software, the FDR's setting can be customized and the raw GPS files (.CAI) can be converted to translated GPS files (.GPS) for post flight processing.

2.2 Post Flight Processing

Each translated GPS file must then be processed for analysis. A graphic view of the flight path, altitudes, and associated velocities for each flight can be viewed through the Cambridge Aero Explorer, Version 1.0 software. These graphic depictions can be very useful in watching a flight in real time, viewing airport traffic pattern entries, analyzing holding patterns, and obtaining an overall snapshot of the flight. However, to perform actual analysis on the flight data, the translated GPS files must be converted to a spreadsheet format for calculations and plot generation.

The UHL Post Flight Processor (PFP) software from U. Harrison Lynch Research Associates, Incorporated was used. The first step was to convert the FRSxxxxx.gps file into an IFLxxxxx.dat file. To do so, the user must specify the appropriate AIRCRAFT.dat, RUNWAYxx.dat, LNDPATxx.dat, GROUNDxx.dat, and WAYPNTxx.dat files to be used. The AIRCRAFT.dat file is the most important, and contains the technical information about the aircraft that was used, including such things as wing area and C_L (coefficient of lift). This information is used by the computer to calculate the dynamic response of the aircraft and smooth the processed data, transforming the 1 Hz data into 10 Hz data. The other files are not mandatory, but add detail to the graphic outputs of the GPHxxxxx.flt files, which will be discussed briefly in the next paragraph. These details include runway widths and lengths, ground objects, waypoints and navigation fixes, as well as ideal traffic patterns and approach paths.

Then the user must enter the graphic output distance, magnetic variation, wind directions and velocity, aircraft type, and the GPS file to be processed. The PFP then creates the IFLxxxxx.dat file. Next, the user must actually process the IFLxxxxx.dat file. This process creates 6-10 additional files, of which only the GPHxxxxx.flt and PLFxxxxx.dat are useful. The others are then deleted. The GPHxxxxx.flt file is used with the UHL Winview software to display the flight visually. The PLFxxxxx.dat file is imported into Microsoft Excel with fixed distance columns for analysis and plot generation.

2.3 Research Method

To familiarize himself with the FDR, the author placed the FDR in the back of his 1996 Toyota Tacoma and collected data. He then took the FDR on a test flight in a

Cessna 152 aircraft at The Ohio State University's Don Scott Airport. After the author was familiar with the FDR and the associated software, research flights were conducted.

The FDR was belted in the back of various Cessna 172 Skyhawk aircraft at the OSU Airport. Various students then flew the FDR on cross-country flights and National Intercollegiate Flying Association (NIFA) navigation runs. Aircraft numbers, flight crew information, and flight details were recorded for documentation purposes. (See Table 2.3) In addition to these flights, a few other flights were recorded which were simply local flights, and were of no interest to this particular research project, but may be later analyzed when more detailed metrics have been developed. (See Table 2.2)

Table 2.2: List of Flight Logs

Flight Log Number	*Description*
00001	UHL Test 1
00002	UHL Test 2
00003	Chevrolet Truck Test 1
00004	Chevrolet Truck Test 2
00005	Toyota Truck Test 1
00006	Toyota Truck Test 2
00007	Toyota Truck Test 3
00008	Toyota Truck Test 4
00009	Local Flight 1
00010	NIFA Nav Run 1
00011	NIFA Nav Run 2
00012	Local Flight 2
00013	Cross-Country 1
00014	Corrupted Data
00015	Cross-Country 2
00016	Cross-Country 3
00017	Local Flight 3
00018	Local Flight 4
00019	NIFA Nav Run 3

Table 2.3: Research Flight Details					
Flight Log Number	*Date*	*Aircraft*	*Flight Crew*	*Description*	*Type*
00010	2/26/2005	N173QS	Pilot/Copilot	NIFA Navigation Run	VFR
00011	2/26/2005	N100SU	Pilot/Copilot	NIFA Navigation Run	VFR
00013	4/4/2005	N65784	Dual	Cross-Country	VFR
00015	4/6/2005	N54628	Solo	Cross-Country	VFR
00016	4/6/2005	N54628	Solo	Cross-Country	VFR
00019	4/9/2005	N100SU	Pilot/Copilot	NIFA Navigation Run	VFR
Flight Log Number	*Waypoint*	*Latitude*	*Longitude*	*Altitude*	*True Course*
		(North)	(West)	*(Feet Above MSL)*	(Degrees)
00010	KOSU	40:04.79	83:04.38	2000	N/A
	Center of Town	40:10.78	83:26.13	2000	285.40
	Power Lines + RR	40:21.50	83:30.00	2000	340.15
	Drag Strip	40:32.00	83:21.83	2000	37.89
	Pvt Strip	40:23.33	83:06.50	2000	119.49
	Bridge	40:14.17	82:58.00	2000	137.14
	KOSU	40:04.79	83:04.38	2000	214.22
00011	KOSU	40:04.79	83:04.38	2000	N/A
	Center of Town	40:10.78	83:26.13	2000	285.40
	Power Lines + RR	40:21.50	83:30.00	2000	340.15
	Drag Strip	40:32.00	83:21.83	2000	37.89
	Pvt Strip	40:23.33	83:06.50	2000	119.49
	Bridge	40:14.17	82:58.00	2000	137.14
	KOSU	40:04.79	83:04.38	2000	214.22
00013	KOSU	40:04.79	83:04.38	5500	N/A
	2G2	40:21.57	80:42.00	5500	83.28
00015	KOSU	40:04.79	83:04.38	4500	N/A
	KPKB	39:20.70	81:26.35	4500	114.22
	KHOC	39:11.33	83:32.33	4500	265.75
00016	KHOC	39:11.33	83:32.33	4500	N/A
	KEDJ	40:22.33	83:49.13	4500	346.69
	KOSU	40:04.79	83:04.38	4500	111.40
00019	KOSU	40:04.79	83:04.38	2000	N/A
	Pvt. Strip	40:08.42	83:23.41	2000	280.80
	Pvt. Strip	40:18.52	83:36.91	2000	306.80
	Pvt. Strip	40:23.04	83:06.41	2000	81.58
	Pvt. Strip	40:17.69	82:43.88	2000	103.36
	Pvt. Strip	40:15.54	83:00.71	2000	262.72
	KOSU	40:04.79	83:04.38	2000	198.85

The flight logs were downloaded, translated, and processed. The flights that were cross-country expeditions and navigation runs were then analyzed. Chapters 3, 4 and 5 provide more specific information on the actual flight analysis.

CHAPTER 3

GRAPHIC DISPLAYS

3.1 Flight Snapshots

Graphic displays create a picture of the flight from above and from the side, allowing the user to watch the aircraft's path over the surface of the earth in real time. The Cambridge Aero Explorer, Version 1.0 software and the UHL Winview software both provide these pictures. By looking at the picture, a viewer can determine if the pilot executed a holding pattern correctly or followed standard landing pattern procedures at an airport. This is especially useful to flight instructors who can determine in a single glance if their student actually went to the correct airport, if the student followed the entry and exit procedures, and if they actually landed. Usually, the instructor can only hope that their student is following the regulations and actually traveling to the intended airport on a solo cross-country flight.

3.2 Flight 00013

This cross-country flight was flown to Jefferson County Airport (2G2), in Steubenville, Ohio. In Figure 3.1, the profile view of the flight is clearly seen. The pilot remained below 2,500 feet to avoid the Columbus Class C airspace, before climbing up to his planned cruising altitude of 5,500 feet. Zooming in on the plan view of this flight,

Figure 3.2 shows the arrival at the airport. The pilot over-flew the field, assessed the winds and traffic pattern, and then entered on the forty-five to the left downwind for Runway 32. This entry was perfectly executed, following all of the procedures in the Aeronautical Information Manual (AIM).

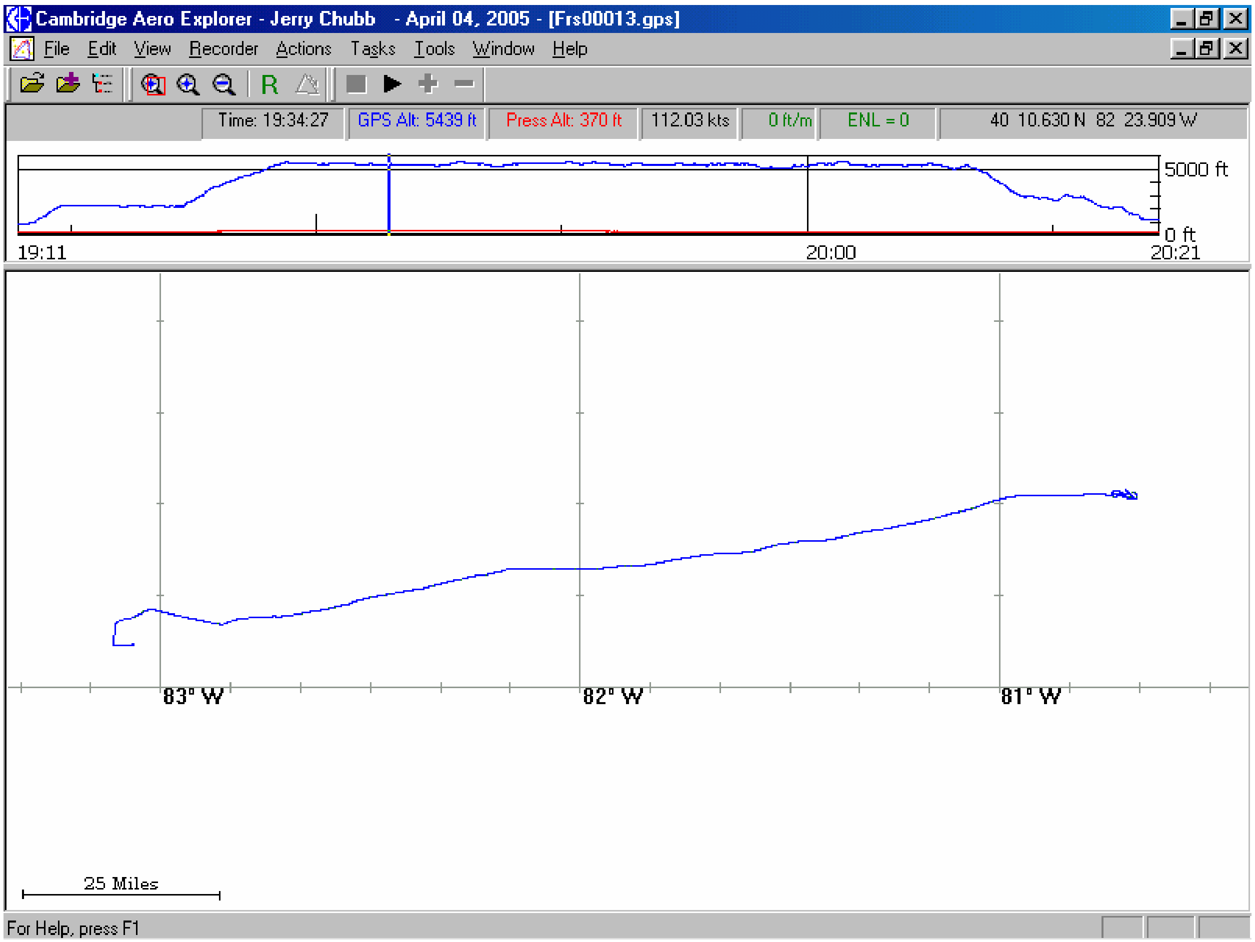


Figure 3.1: Flight 00013 - Overview

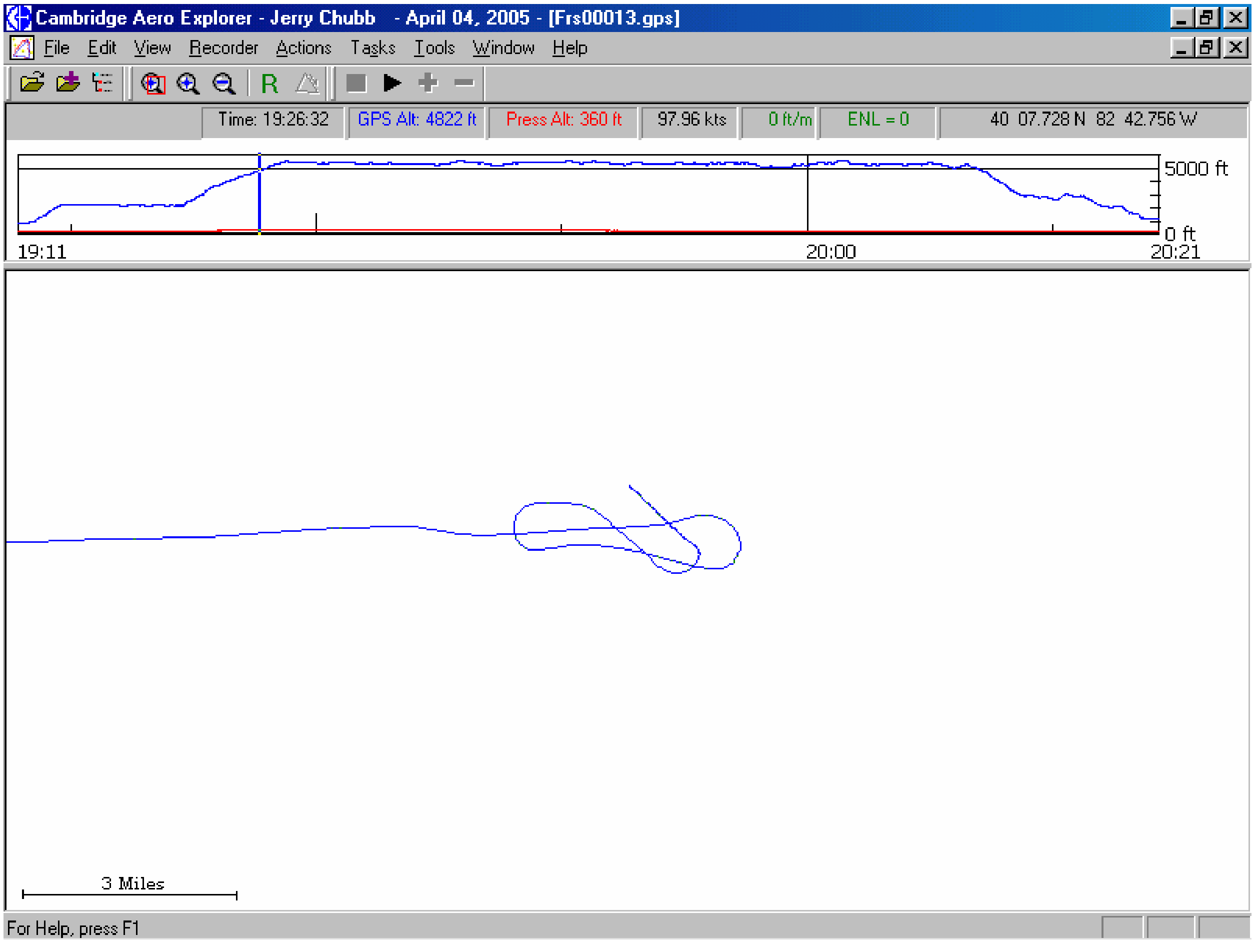


Figure 3.2: Flight 00013 - Entry

3.3 Flight 00015

This cross-country flight included two different destinations. The first was Mid-Ohio Valley Regional Airport (KPKB), near Marietta, Ohio and Parkersburg, West Virginia. In Figure 3.3, the entry to the traffic pattern can be seen in the plan view. There is no forty-five to the downwind and the traffic pattern is to the right. This would be incorrect at most uncontrolled fields, but KPKB has a control tower and is designated as Class D airspace, making this entry correct. The second stop was made on a flight to Highland County Airport (KHOC) in Hillsboro, Ohio. It can be seen in figure 3.4 that the pilot did not fly over the field to assess the winds and traffic pattern, but probably listened to the AWOS-3 that is on the field, monitored the CTAF frequency, and then entered on the forty-five to the left downwind for Runway 23. The forty-five to the downwind looks to be a little short of midfield downwind, and is very short in length, but this entry is again satisfactory.

Figure 3.3: Flight 00015 - Overview

Figure 3.4: Flight 00015 - Entry

3.4 Flight 00016

This flight is made to Bellefontaine Regional Airport (KEDJ) in Bellefontaine, Ohio. In Figure 3.6, it can be seen that the entry to the traffic pattern was made on the forty-five to the left downwind for Runway 22. It is again assumed that the pilot listened to the AWOS-3 and monitored the CTAF frequency, making a flight over the field unnecessary, and allowing this entry to the airport's traffic pattern correct. In Figure 3.5, the entire flight can be seen, and the last airport is Ohio State University Airport (KOSU). It is a controlled field, so the traffic pattern entry is correct, even though it is not standard.

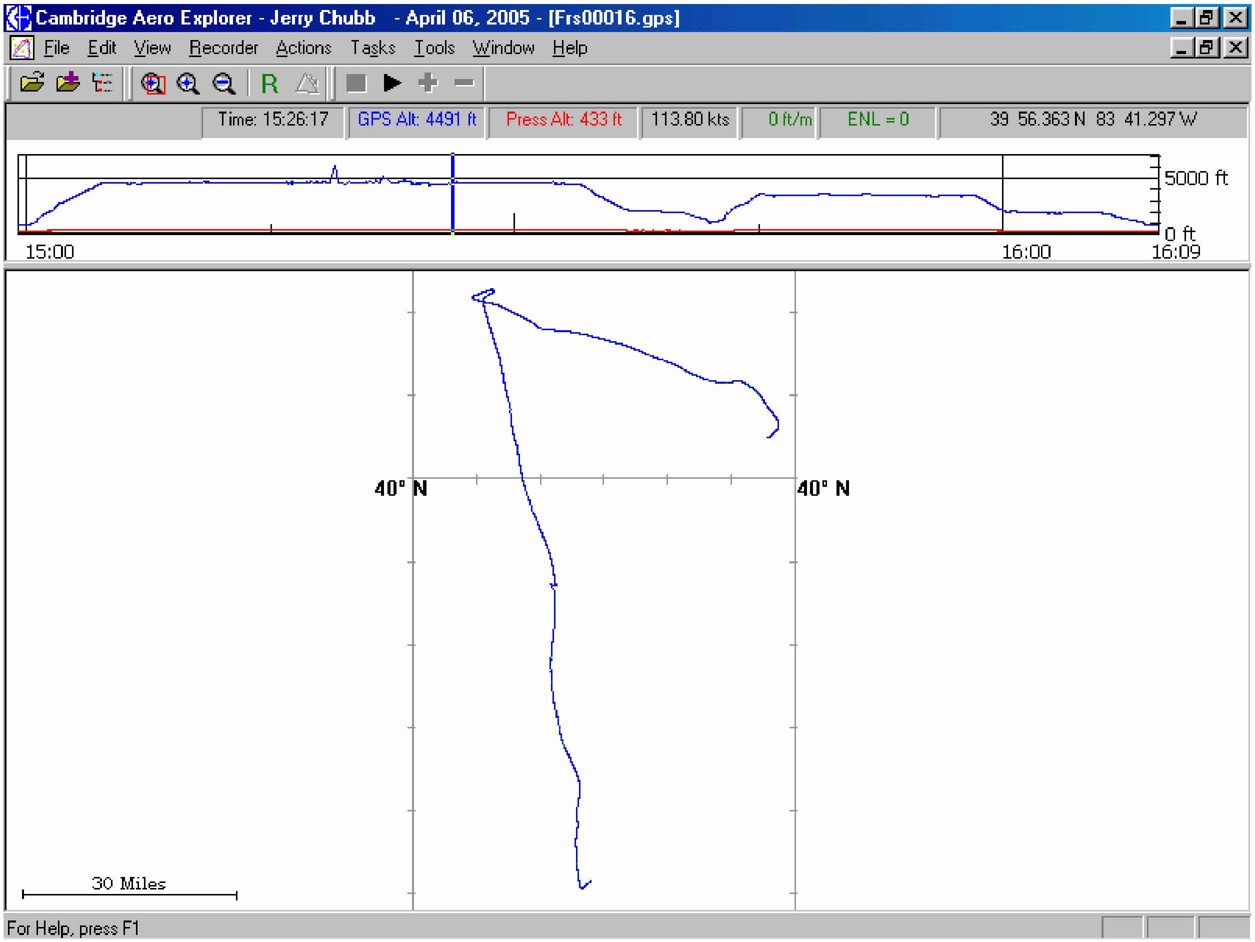


Figure 3.5: Flight 00016 - Overview

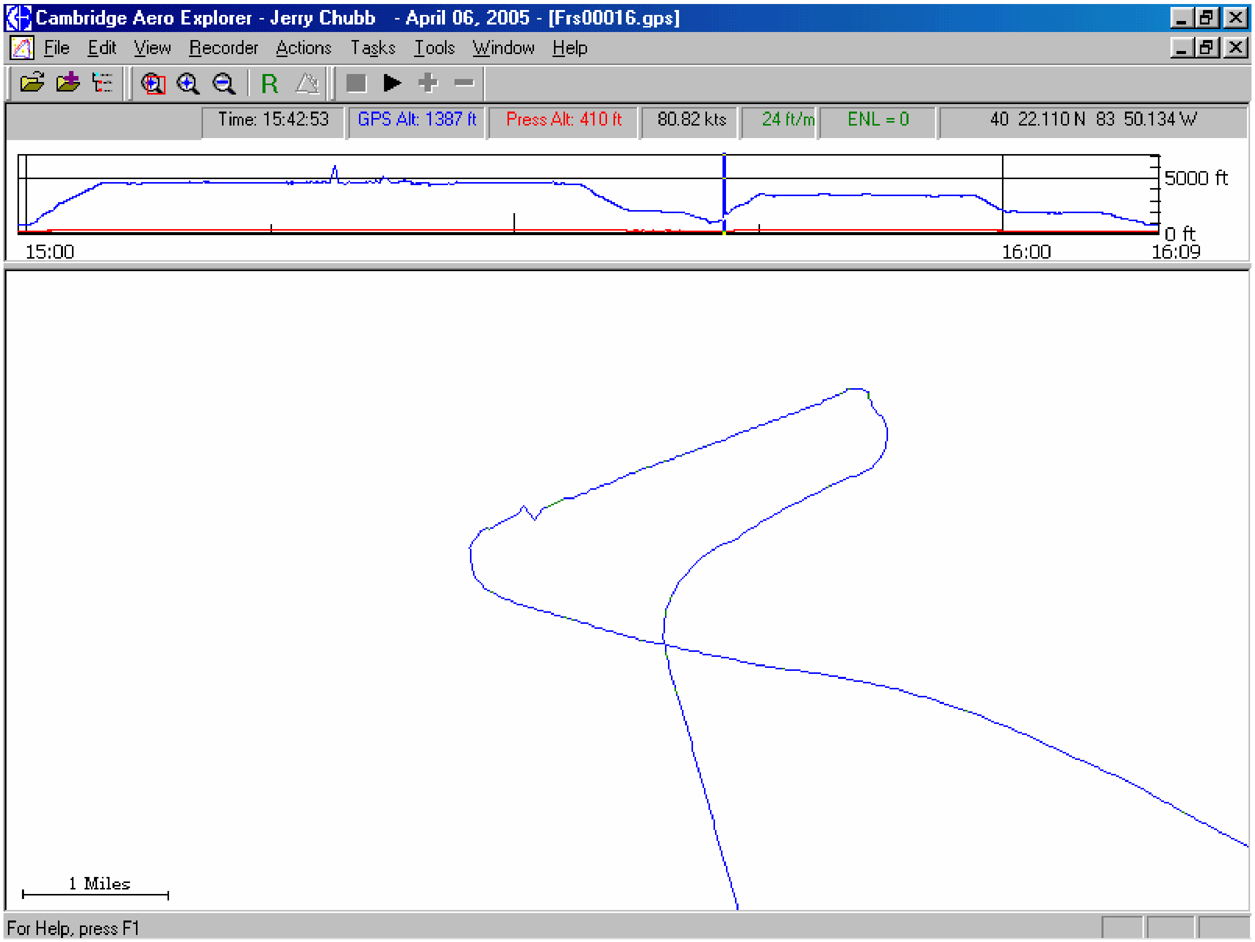


Figure 3.6: Flight 00016 - Entry

CHAPTER 4

ALTITUDE ANALYSIS

4.1 Introduction

The ability of a pilot to maintain an assigned altitude is paramount to the safety of everyone operating in the airspace environment. Aircraft generally cruise at 500 to 1000 foot intervals, depending on altitude, starting from the ground all the way up to altitudes in excess of 10 miles. Under the newly instituted rules of Reduced Vertical Separation Minima (RVSM), this distance between cruising altitudes has been decreased by half in certain areas. Traffic which is operating under visual flight rules (VFR) cruise at the 500 foot levels, while traffic operating under instrument flight rules (IFR) cruise at the 1000 foot levels. This provides for a separation of at least 500 feet in altitude between IFR and VFR aircraft traveling in various directions. While VFR aircraft are kept separated by Air Traffic Control (ATC) Specialists (ATCS), advisory services to VFR aircraft are only provided upon request and when workload permits. VFR aircraft on the same airway can often meet head-on in the vicinity of radio navigation aids.

When pilots have passed the specified FAA written tests, they take practical tests, which consist of both oral exams and in-flight evaluations. The examiner is required to hold the pilot candidate to within 100 feet of his planned or FAA assigned altitude (FAA Private Pilot PTS, 1-21). This criteria is also used as the standard for day to day flight operations. This means that if a pilot is operating 100 feet below where he is supposed to be, and another is operating 100 feet above, within the standards set by the FAA, suddenly the 500 feet of separation is cut to a mere 300 feet. An error in altimeter setting, instrument indication, or pilot performance can decrease this margin even further, and could lead to a midair collision. In addition, the FAA allows an altimeter to be off by 75 feet and still be considered functional for flight into Instrument Meteorological Conditions (IMC). If one pilot was operating at the edge of his 100 foot envelope with this 75 foot error added on, and another pilot was doing the same thing, it would be possible for them to pass within 150 feet of one another. Ideally, no pilot would be operating at the edge of the altitude window, but a fully qualified pilot may be permitted these errors, and perhaps more. That leaves unanswered the question: What are the chances of a pilot breaking this 100 foot limit?

To answer this question, each flight was examined, and the flight segment in which the aircraft was at cruising altitude was analyzed. Plots were made of the pilot's altitude versus time and altitude deviation frequencies. Standard deviations and percentages were calculated to analyze each pilot's performance.

4.2 Flight 00010

Flight 00010 was flown by two pilots on a practice National Intercollegiate Flying Association (NIFA) navigation run. Table 2.3 provided full flight information for this navigation run. The altitude plot for the flight is contained in Figure 4.1. The zero line on the y-axis represents the target altitude, which was 2000 feet above mean sea level

(MSL).

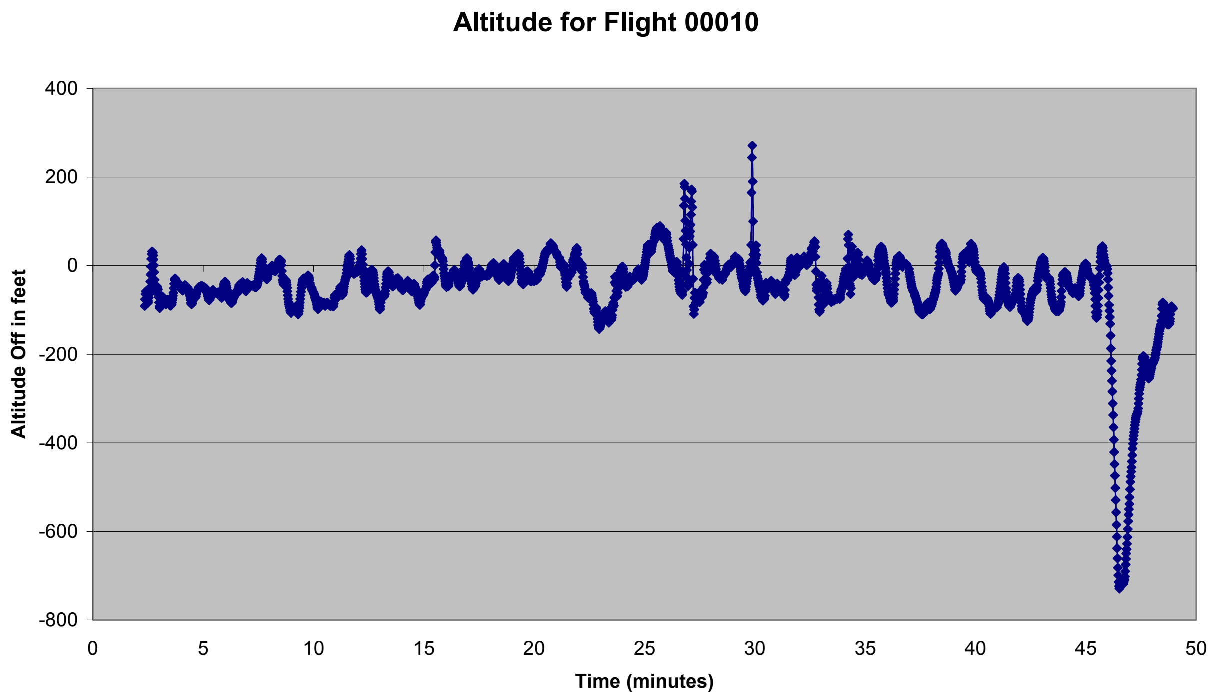


Figure 4.1

Throughout the duration of the flight, the pilot maintained his altitude, with deviations above and below the target altitude. There are two fairly large positive spikes in the plot, which represent large gains in altitude. There is also an abnormally large negative spike in altitude towards the end of the data set which represents a loss of altitude in excess of 750 feet. These spikes are interesting, and could possibly represent significant pilot error, an evasion or training maneuver, or a GPS anomaly, although no indication of the latter exists. While these anomalies are included, the altitude frequency distribution will look semi-normal and is contained in Figure 4.2.

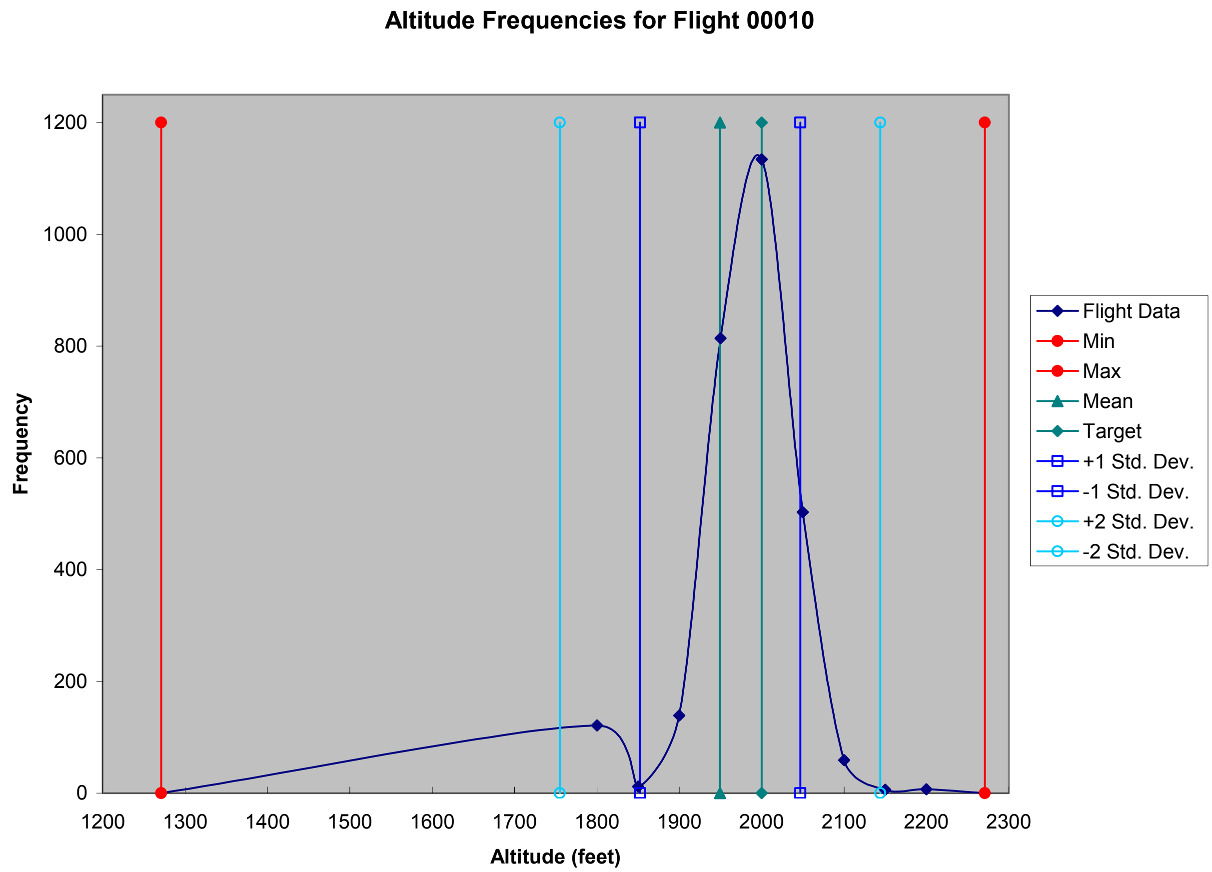


Figure 4.2

From this data, it can be determined that the pilot's average or mean altitude was 1950 feet MSL. This means that the pilot was consistently 50 feet below his target altitude, which could be a result of non-standard temperature, incorrect altimeter setting, instrument error, or pilot error. It can also be concluded that the pilot was within 100 feet of his target altitude 89.81% of the time he was at cruising altitude. So for over 10% of the time he was at cruising altitude, or 4 minutes and 48 seconds, he was outside of his 100 foot window.

If a normal distribution of the data is assumed, despite the large tail on the left side of the graph which was the result of the large negative spike in Figure 4.1, a Z value of 1.03 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 30.30% chance that the pilot will exceed the 100 foot limit above or below his target altitude (Hicks, 312-313).

If the large negative spike in altitude is disregarded, the frequency distribution changes to the almost perfectly normal distribution in Figure 4.3.

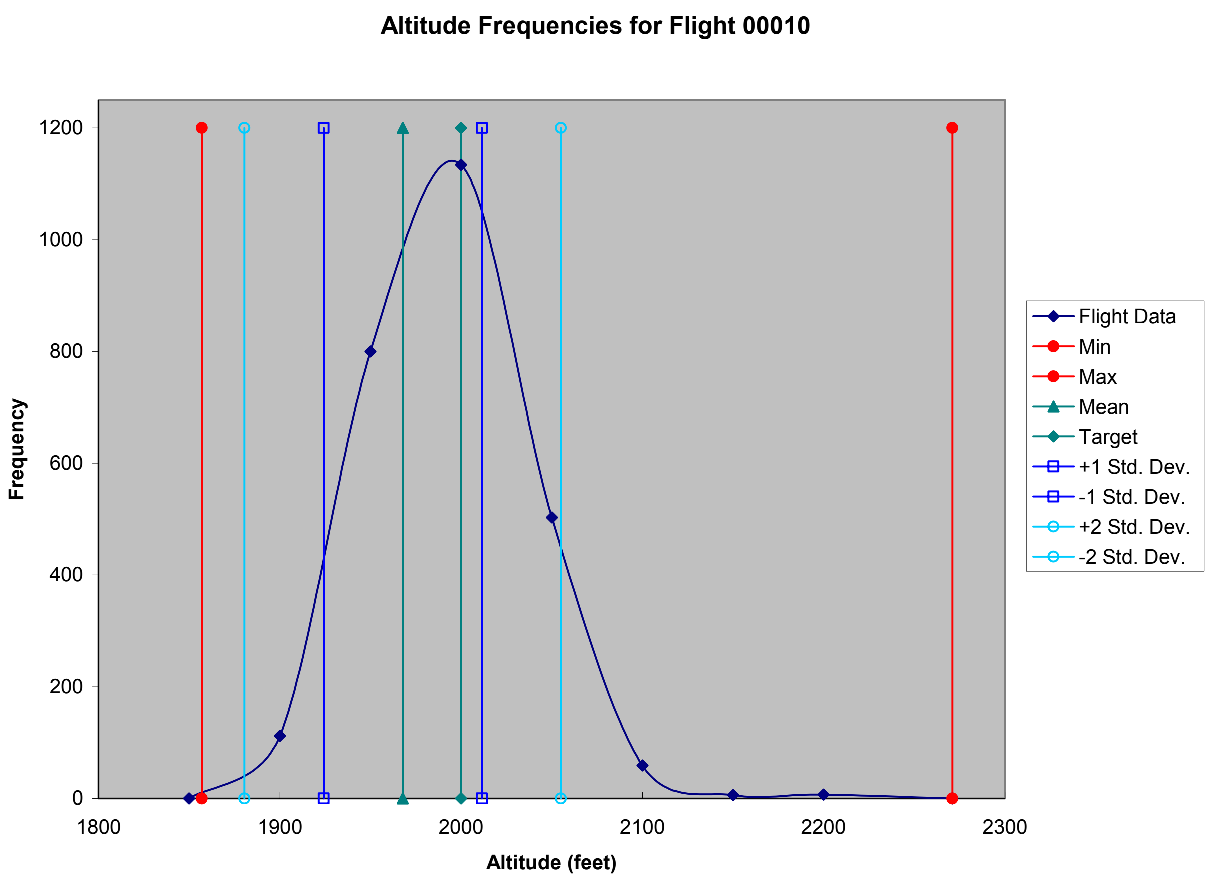


Figure 4.3

The pilot's new mean altitude is 1968 feet MSL, only 32 feet below the target altitude. The pilot spent 95.23% of the flight within 100 feet of his target altitude, or 2 minutes and 8 seconds of the almost 44 minute flight in excess of 100 feet of the target altitude. The new Z value is 2.29, which means that the pilot only has a 2.20% probability of exceeding the 100 foot altitude limit.

4.3 Flight 00011

Flight 00011 was flown by the author with another pilot on a practice NIFA navigation run. Table 2.3 provided full flight information for this navigation run. The altitude plot for the flight is contained in Figure 4.4. The zero line on the y-axis represents the target altitude, which was 2000 feet MSL.

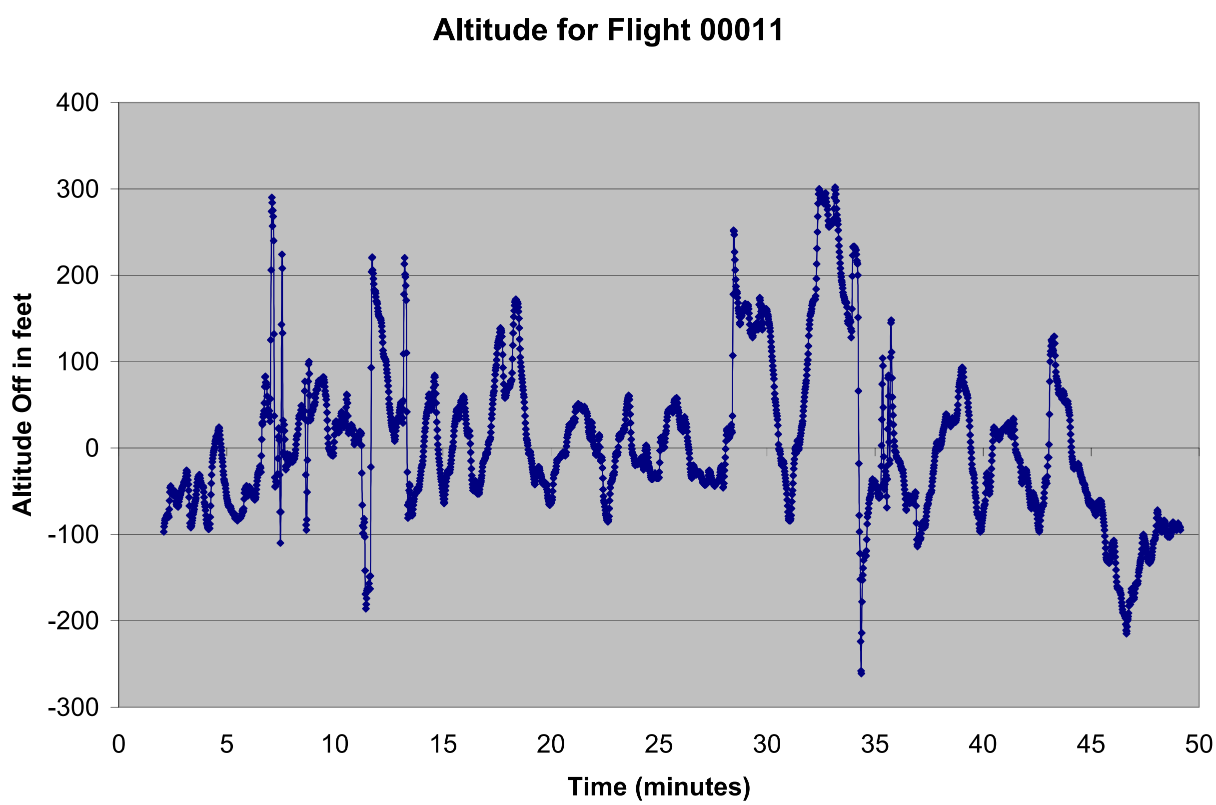


Figure 4.4

Throughout the duration of the flight, the pilot maintained his altitude, with deviations above and below the target altitude. Several spikes are visible, but none are greater than

300 feet. The altitude frequency distribution is approximately normal, and is contained in Figure 4.5.

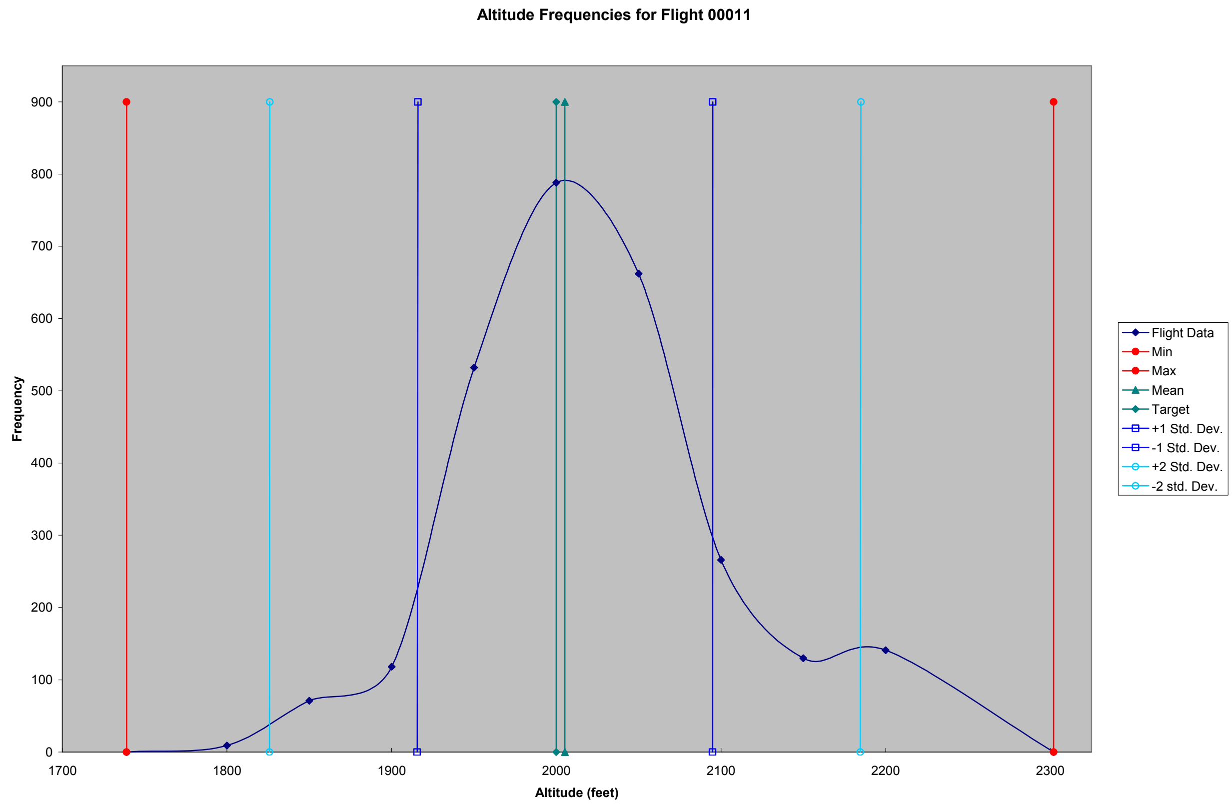


Figure 4.5

From this data, it can be determined that the author's mean altitude was 2005 feet MSL. It can also be concluded that the author was within 100 feet of his target altitude 79.74% of the time he was at cruising altitude. So for over 20% of the time he was at cruising altitude, or 9 minutes and 25 seconds, he was outside of his 100 foot window.

If a normal distribution of the data is assumed, a Z value of 1.11 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 26.7% chance that the pilot will exceed the 100 foot limit above or below his target altitude (Hicks, 312-313).

4.4 Flight 00013

Flight 00013 was flown by a primary student and their certified flight instructor (CFI) on a cross-country training flight from The Ohio State University Airport (KOSU), Columbus, Ohio to Jefferson County Airpark (2G2), Steubenville, Ohio. Table 2.3 again provides full flight information for this cross-country. The altitude plot for the flight is contained in Figure 4.6. The zero line on the y-axis represents the target altitude, which was 5500 feet MSL.

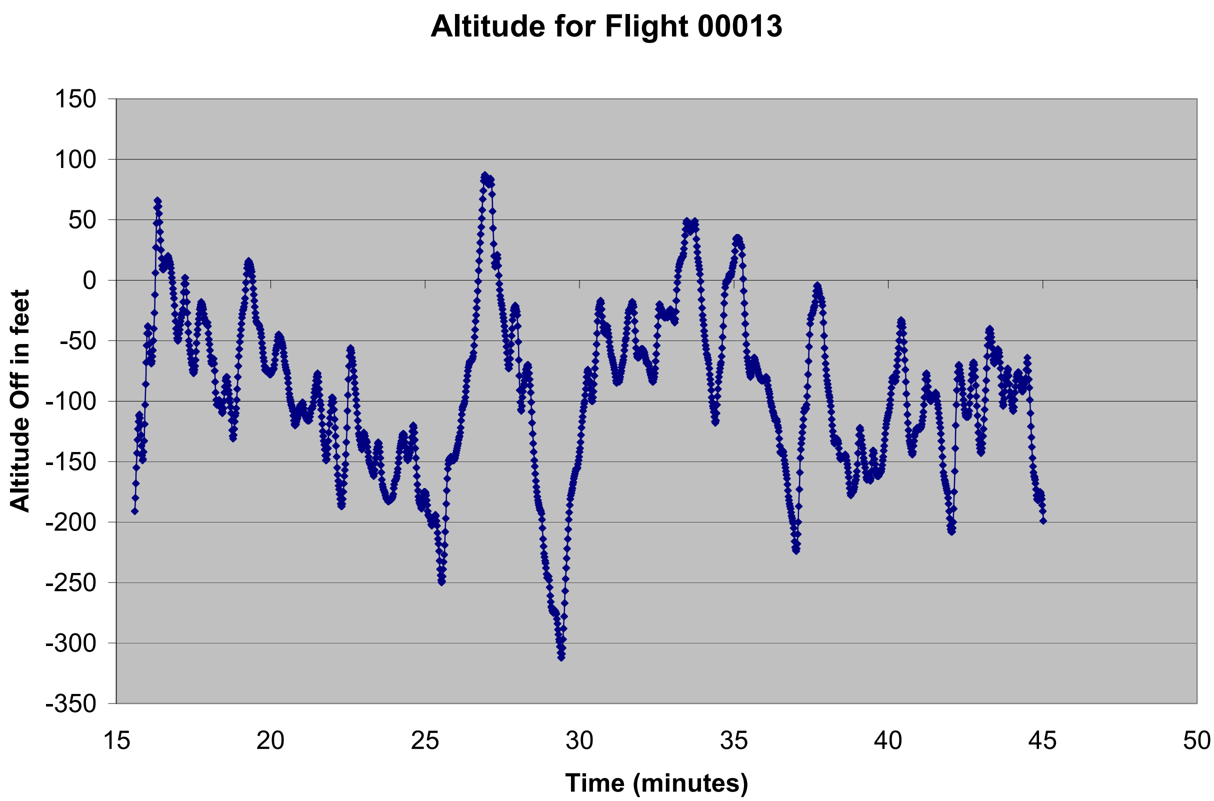


Figure 4.6

Throughout the duration of the flight, the pilot maintained his altitude, with deviations above and below the target altitude. Several large deviations are visible. The altitude frequency distribution is approximately normal, and is contained in Figure 4.7.

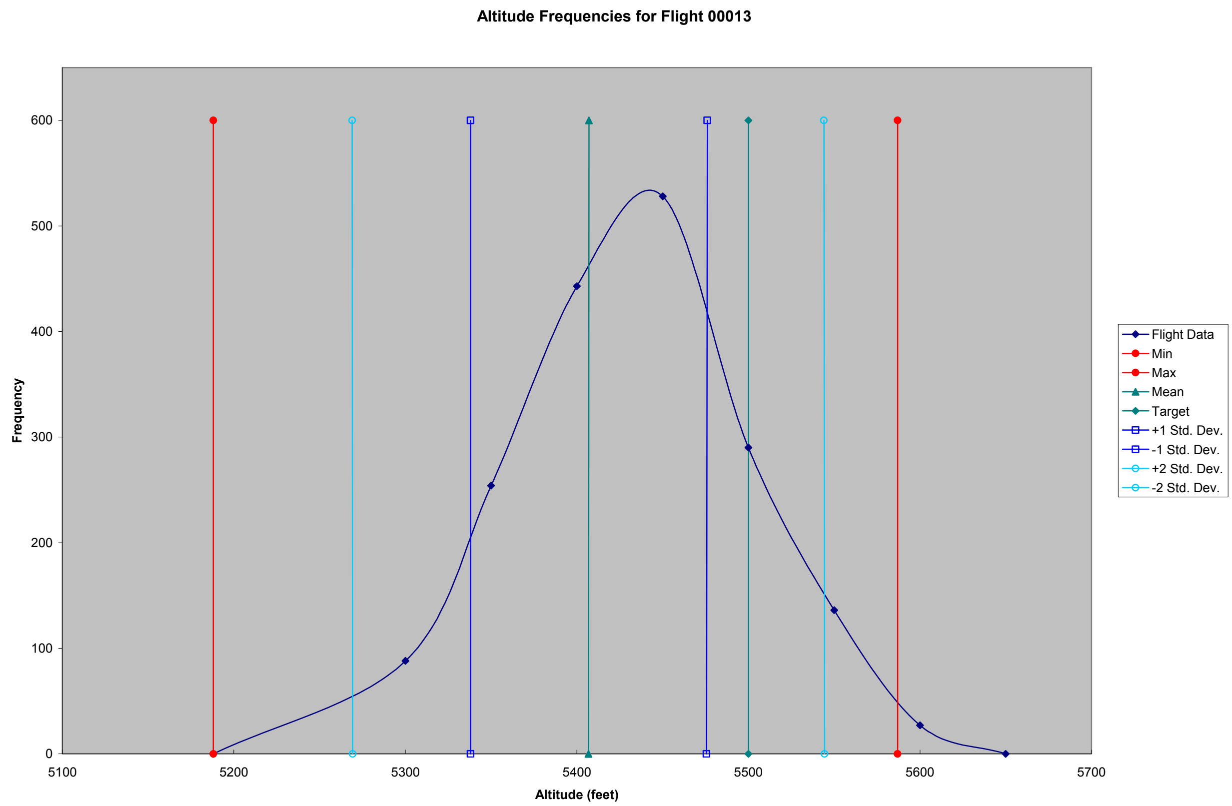


Figure 4.7

From this data, it can be determined that the pilot's average or mean altitude was 5407 feet MSL. This means that the pilot was consistently almost 100 feet below his target altitude, which could be a result of non-standard temperature, incorrect altimeter setting, instrument error, or pilot error. In this particular case, it is likely to be the result of pilot error combined with other errors, as this was a student pilot on his first cross-country at the time of the flight. Regardless of cause, it can be concluded that the pilot was within 100 feet of his target altitude 55.58% of the time he was at cruising altitude. So for over 44% of the time he was at cruising altitude, or 13 minutes and 4 seconds, he was outside of his 100 foot window.

If a normal distribution of the data is assumed, a Z value of 1.45 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 14.7% chance that the pilot will exceed the 100 foot limit above or below his target altitude (Hicks, 312-313). There is a large difference between the fact that at any given time there is a 14.7% chance that the pilot will be beyond 100 feet of his target altitude and that the pilot was actually outside of this 100 foot window 55.58% of the time. At first, this looks very contradictory, but upon closer examination, it is apparent that while the pilot was often outside the 100 foot window, he never deviated more than 90 feet above or 320 feet below, and was often just outside the 100 foot window, which leads to the fairly good Z score.

4.5 Flight 00015

Flight 00015 was a solo cross-country training flight from The Ohio State University Airport (KOSU), Columbus, Ohio to Mid-Ohio Valley Regional Airport (KPKB), Parkersburg, West Virginia to Highland County Airport (KHOC), Hillsboro, Ohio. Again, Table 2.3 provides the information for this cross-country flight. The altitude plot for the flight is contained in Figure 4.8. The zero line on the y-axis represents the target altitude, which was 4500 feet MSL.

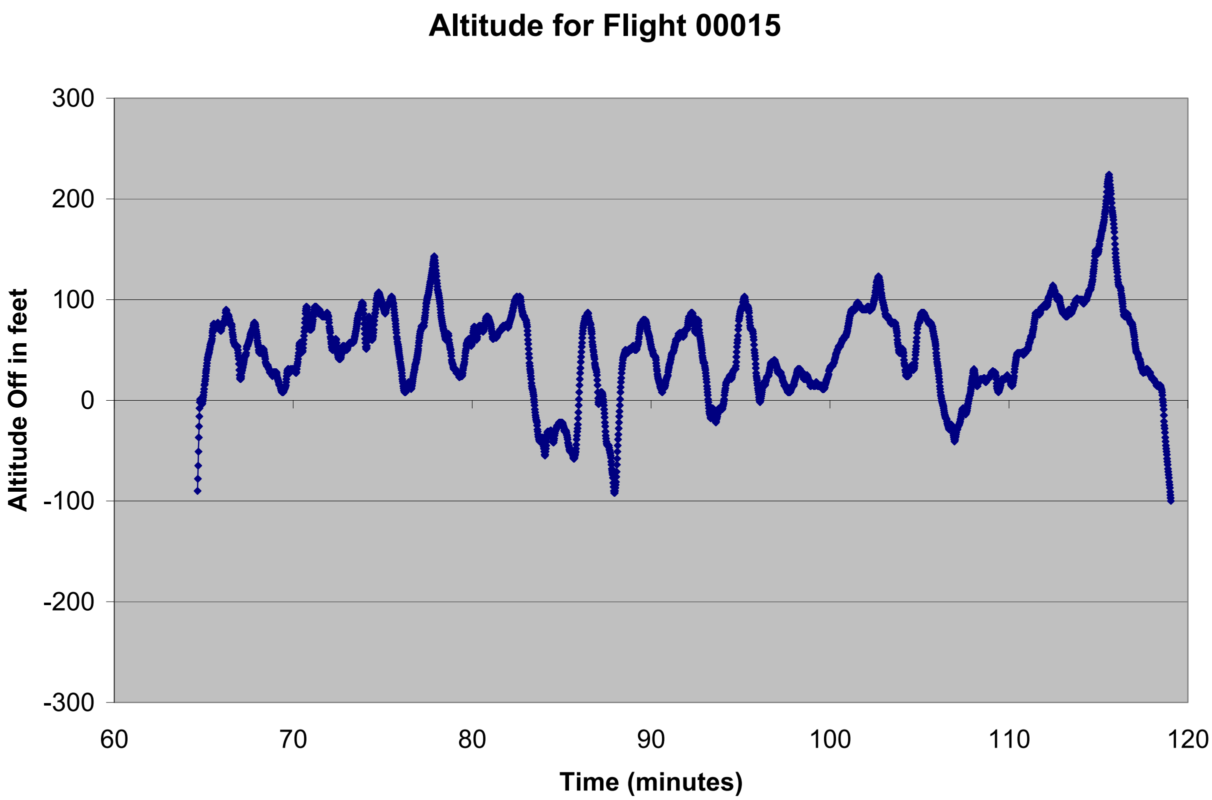


Figure 4.8

Throughout the duration of the flight, the pilot maintained his altitude, with deviations above and below the target altitude. The altitude frequency distribution is approximately normal, and is contained in Figure 4.9.

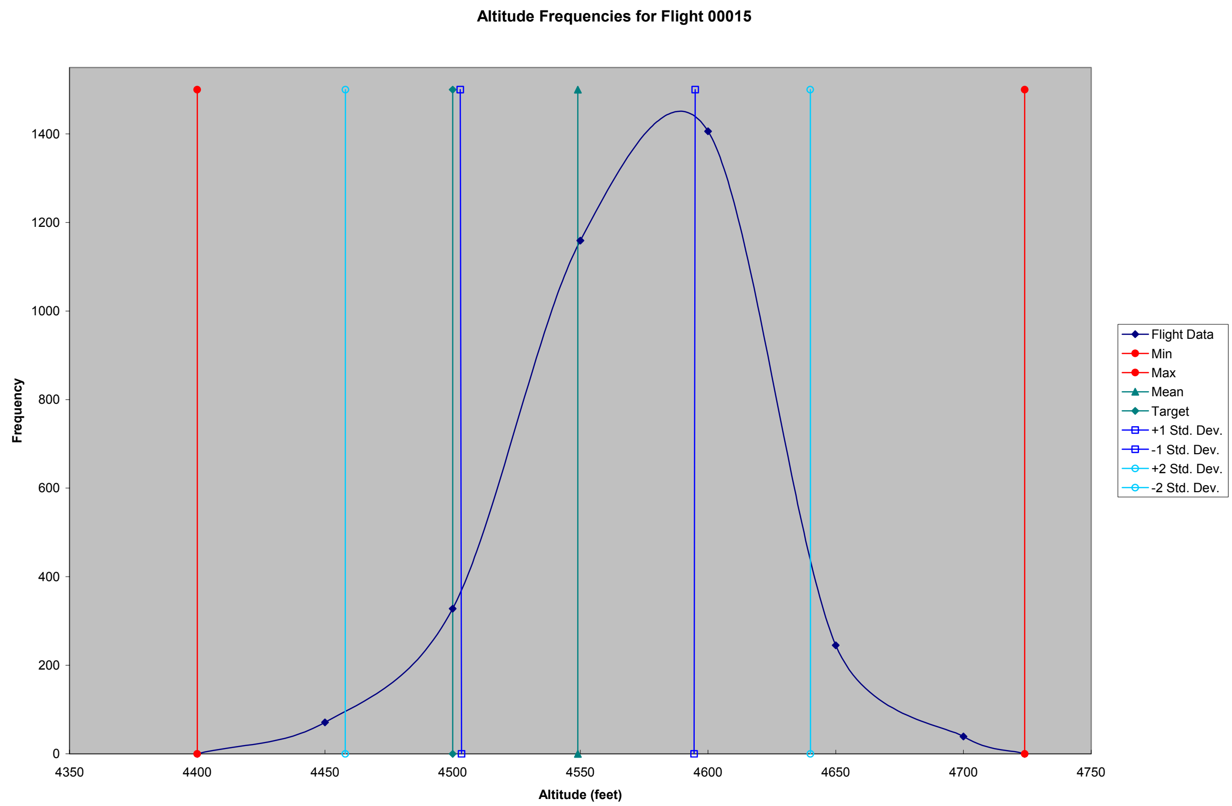


Figure 4.9

From this data, it can be determined that the pilot's mean altitude was 4549 feet MSL. This means that the pilot was consistently almost 50 feet above his target altitude, which could be a result of non-standard temperature, incorrect altimeter setting, instrument error, or pilot error. Regardless of cause, it can be concluded that the pilot was within 100 feet of his target altitude 92.1% of the time he was at cruising altitude. So for only 8% of the time he was at cruising altitude, or 4 minutes and 22 seconds, he was outside of his 100 foot window.

If a normal distribution of the data is assumed, a Z value of 2.2 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 2.78% chance that the pilot will exceed the 100 foot limit above or below his target altitude (Hicks, 312-313).

4.6 Flight 00016

Flight 00016 was flown by the same pilot that was in command of Flight 00015. This flight was a cross-country training flight from Highland County Airport (KHOC), Hillsboro, Ohio to Bellefontaine Regional Airport (KEDJ), Bellefontaine, Ohio to The Ohio State University Airport (KOSU), Columbus. Table 2.3 provides full flight information. The altitude plot for the flight is contained in Figure 4.10. The zero line on the y-axis represents the target altitude, which was 4500 feet MSL.

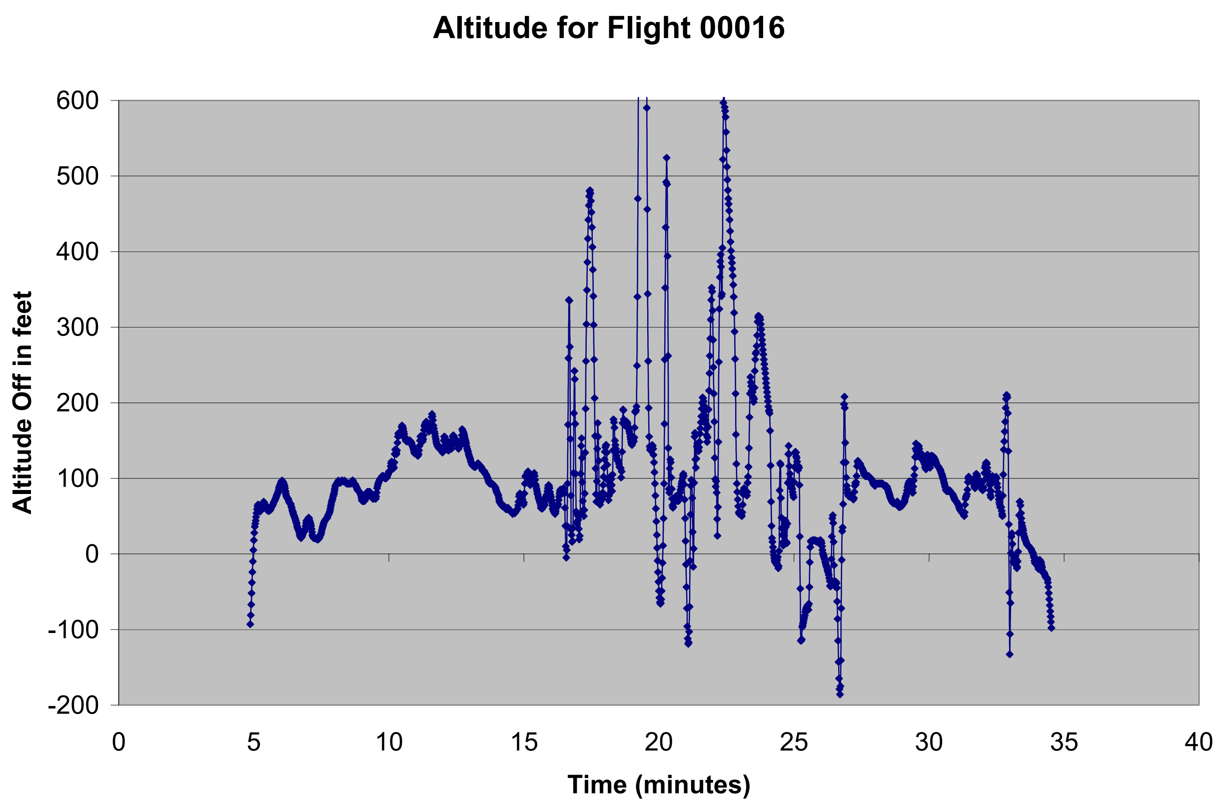


Figure 4.10

Throughout the duration of the flight, the pilot maintained his altitude, with deviations above and below the target altitude. The altitude frequency distribution is approximately normal, and is contained in Figure 4.11.

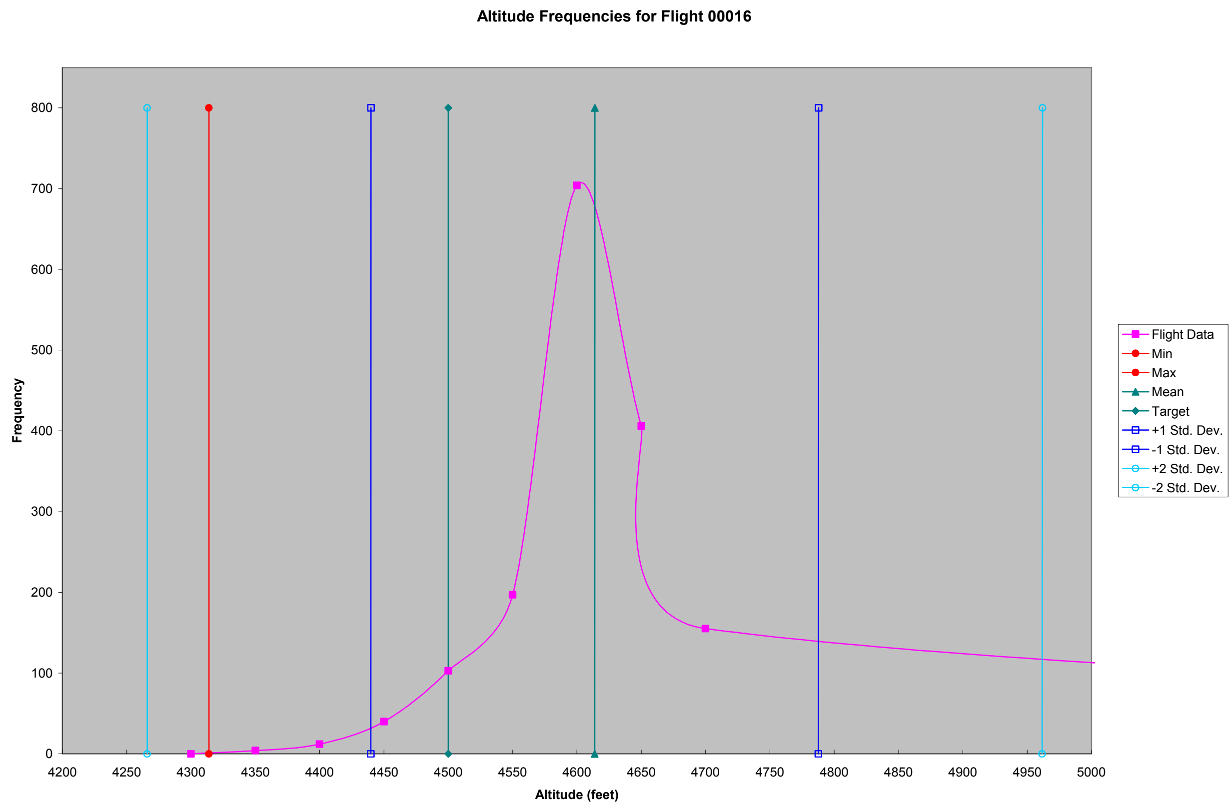


Figure 4.11

From this data, it can be determined that the pilot's mean altitude was 4614 feet MSL. This means that the pilot was consistently almost 115 feet above his target altitude, which could be a result of non-standard temperature, incorrect altimeter setting, instrument error, or pilot error. Regardless of cause, it can be concluded that the pilot was within 100 feet of his target altitude only 59.55% of the time he was at cruising altitude. So for a little over 40% of the time he was at cruising altitude, or 12 minutes, he was outside of his 100 foot window.

If a normal distribution of the data is assumed, a Z value of 0.58 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 56.2% chance that the pilot will exceed the 100 foot limit above or below his target altitude (Hicks, 312-313).

This flight was flown by the same pilot, in the same aircraft, on the same day, in the same state as was Flight 00015. However, there is a huge difference between the data sets. The first flight, 00015, has relatively constant altitude readouts, while the data from Flight 00016 is very erratic. It is possible that there was a GPS anomaly during the second flight, although there is no evidence in the raw GPS data of one occurring. The battery could have been getting low, but this never caused any of the same readouts in any other data set. Another possibility is that the pilot became fatigued and started making large altitude deviations. One final possibility is that as the day progressed, the atmosphere became less stable, and turbulence was encountered. Whatever the cause of the large altitude deviations, this pattern is not seen in any of the other data sets, including both the sets used for this project and the sets that were not used.

4.7 Flight 00019

Flight 00019 was flown on a practice NIFA navigation run. Table 2.3 provides full flight information. The altitude plot for the flight is contained in Figure 4.12. The zero line on the y-axis represents the target altitude, which was 2000 feet MSL.

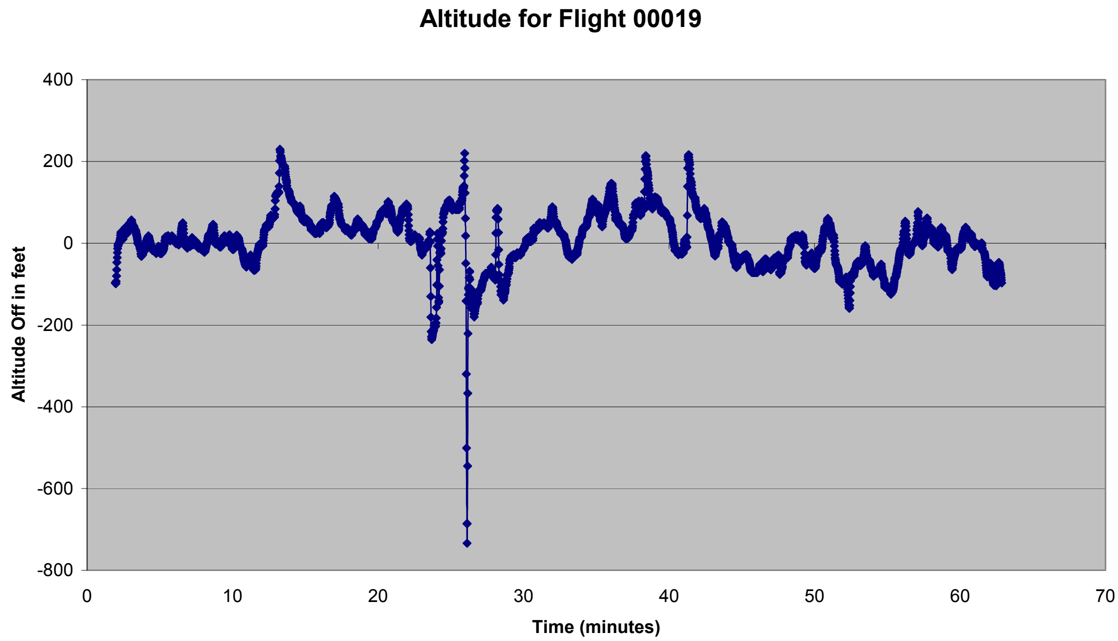


Figure 4.12

Throughout the duration of the flight, the pilot maintained his altitude, with deviations above and below the target altitude. Several spikes are visible, with one especially large negative one about one third of the way through the flight. This spike is interesting, and could possibly represent significant pilot error, an evasion or training maneuver, or a GPS anomaly, although no indication of the latter exists. The altitude frequency distribution is approximately normal, and is contained in Figure 4.13.

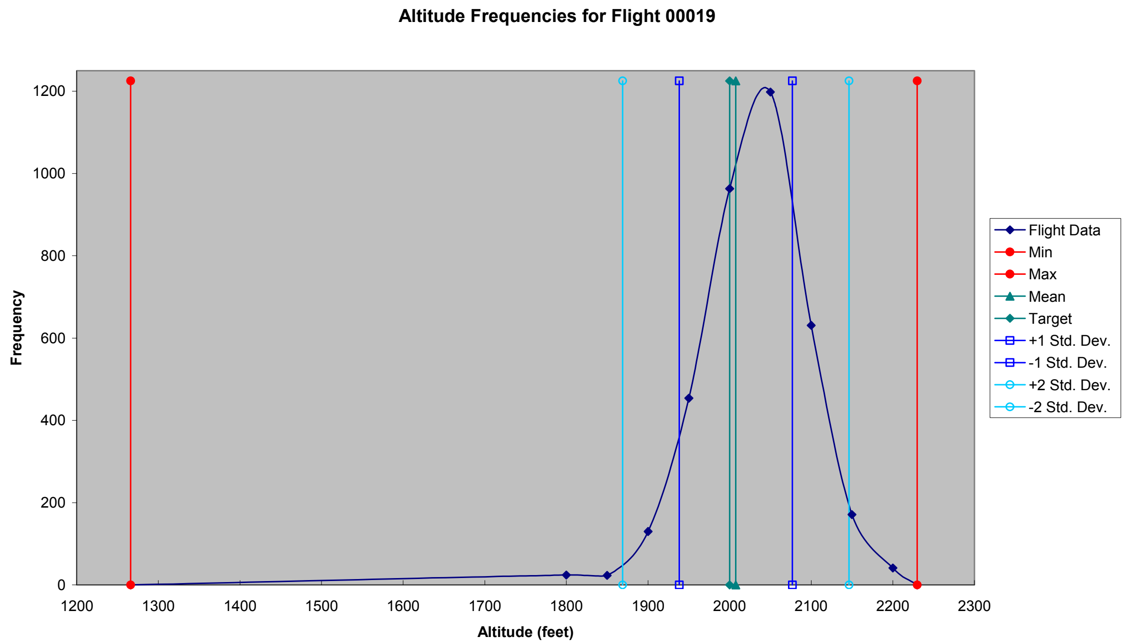


Figure 4.13

From this data, it can be determined that the pilot's mean altitude was 2008 feet MSL. It can also be concluded that the pilot was within 100 feet of his target altitude 89.11% of the time he was at cruising altitude. So for over 10% of the time he was at cruising altitude, or 6 minutes and 38 seconds, he was outside of his 100 foot window.

If a normal distribution of the data is assumed, a Z value of 1.44 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 14.98% chance that the pilot will exceed the 100 foot limit above or below his target altitude (Hicks, 312-313).

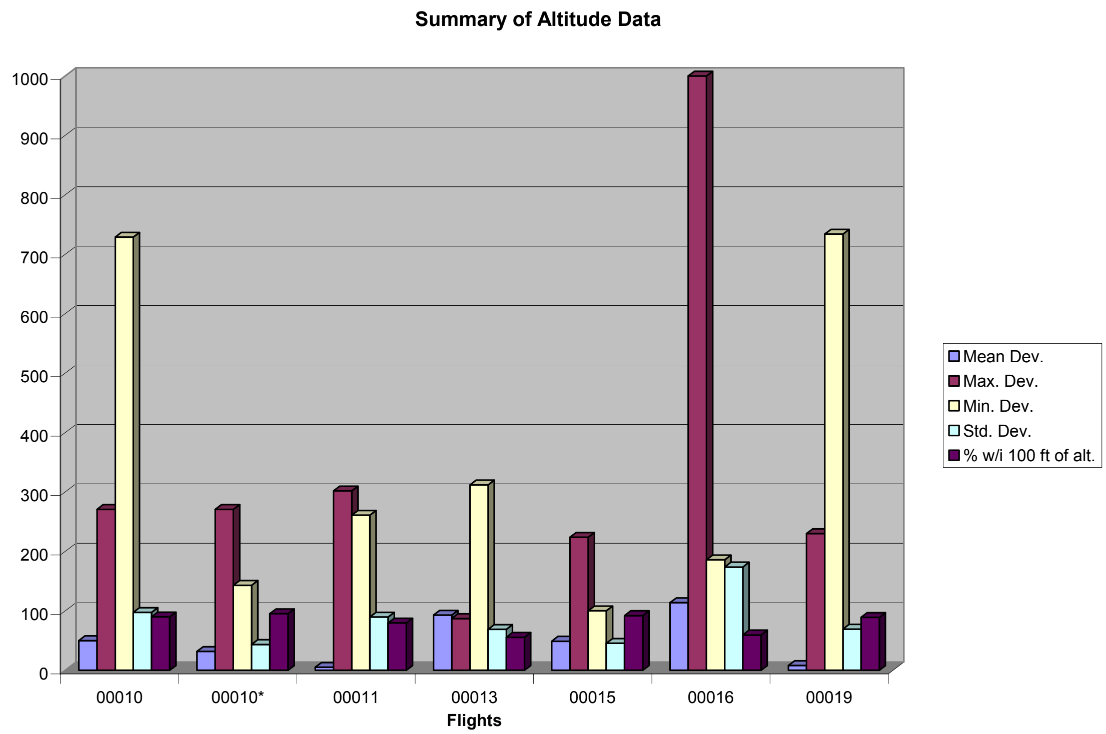
4.8 Conclusions

After analyzing the data, which is summarized in Figure 4.14 and Table 4.1, it was found that there are two main components to evaluating a pilot's ability to maintain an altitude.

Flight		Target Alt.	Mean Alt.	Max Alt.	Min Alt.	Std Dev	w/i 100 (%)	Z Score	Table Look Up	Remain w/i 100 ft (%)	Exceed 100 ft (%)
00010		2000	1950	2271	1271	97.29	89.81	1.03	0.8485	69.70	30.30
00010	*	2000	1968	2271	1857	43.64	95.23	2.29	0.9890	97.80	02.20
00011		2000	2005	2302	1739	89.69	79.74	1.11	0.8665	73.30	26.70
00013		5500	5407	5587	5188	68.79	55.58	1.45	0.9265	85.30	14.70
00015		4500	4549	4724	4400	45.54	92.10	2.20	0.9861	97.22	02.78
00016		4500	4614	6538	4314	173.91	59.55	0.58	0.7190	43.80	56.20
00019		2000	2008	2230	1266	69.35	89.11	1.44	0.9251	85.02	14.98

* Large Negative Deviation Removed

Table 4.1: Summary of Altitude Data



*Large Negative Deviation Removed

Figure 4.14

One measure is the pilot's actual ability to maintain an altitude, which is based solely off the percentage of a flight where the pilot is within 100 feet, above or below, of his target altitude. The other measure is based off the pilot's deviations from the target altitude, which allows for a Z score to be computed and the chance of a deviation to be determined. The Z Score varies only with standard deviation, in this case, because the 100 foot altitude limit is fixed. While there is a relationship between standard deviation and the chance that the pilot will exceed the 100 foot limit, at first glance there seems to be no relationship between a pilot's percentage within 100 feet of the target altitude and the pilot's percentage within 100 feet of the target altitude, if all of the data is considered, as in Figure 4.15.

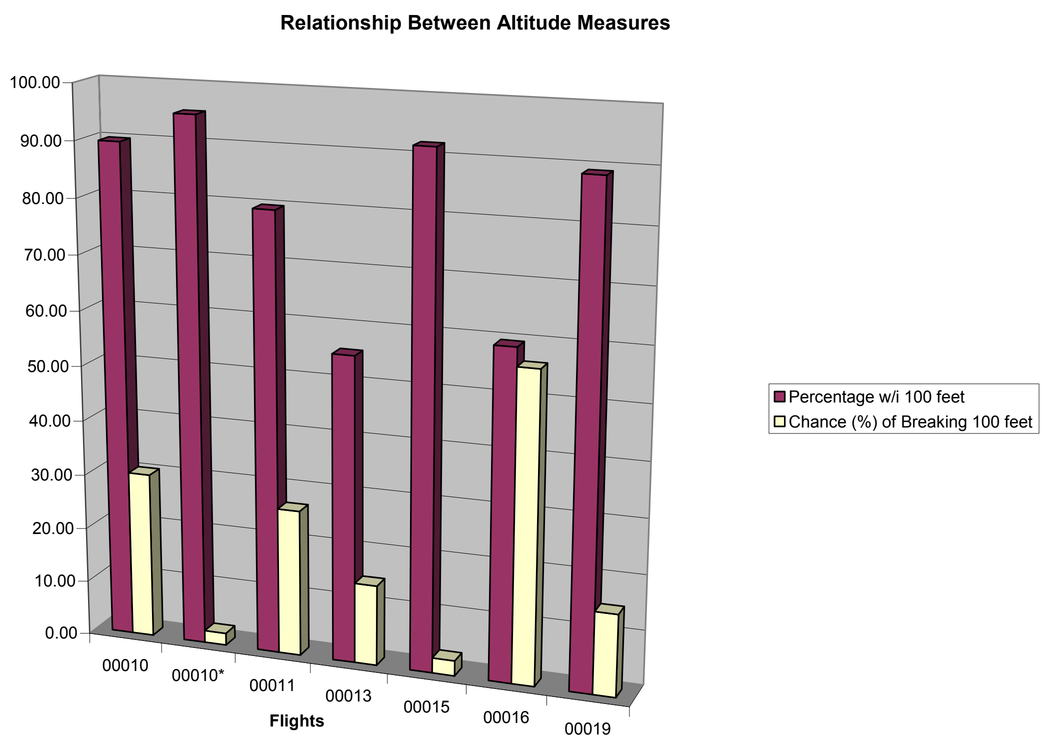


Figure 4.15

However, if Flight 00010 and Flight 00013 are removed from the data set, but Flight 00010* is retained, this conclusion is changed. Flight 00010 can be thrown out because of the large negative spike that occurred towards the end of the flight, and Flight

00013 represents a student on his very first cross-country flight, which may introduce some unknown behaviors such as instructor intervention into the data. After these flights are removed, there is a very clear inverse relationship between the two measures of a pilot's ability to maintain altitude. This is expected, since a pilot that spends most of a flight within 100 feet of the target altitude would probably have few deviations, and a lower chance of breaking this limitation.

CHAPTER 5

GROUND TRACK ANALYSIS

5.1 Introduction

The ability of a pilot to maintain a ground track is important to navigation, which is an essential skill to any aviator. Aircraft generally cruise from place to place on federal airways, GPS direct tracks, and planned azimuth courses. A course is simply an imaginary line from a starting point to ending point. During extremely long flights, this course will look curved when seen on a 2 dimensional surface, because of the curvature of the earth. However, for shorter distances, such as those flown by a typical general aviation pilot, even on a long cross-country, it is a series of straight line segments.

The course line can be based on either True North or Magnetic North. The angle that is formed between the earth's magnetic field and True North is called variation, and has been mapped for the entire globe. The variation changes over time, due to the "floating" of the magnetic North Pole. In every aircraft, there is a magnetic compass that points towards Magnetic North. Inside the cockpit, there are other magnetic fields that may interfere with the compass. This interference is know as deviation, and is documented for each aircraft. A pilot must consider both magnetic variation and compass deviation in order to fly the appropriate compass course to fly along the true course line.

In addition, wind may push the aircraft laterally, so the wind direction and velocity must be determined in order to calculate an appropriate wind correction angle to keep the aircraft on course. When a wind correction angle is added or subtracted from the compass course, the pilot now has a compass heading to fly to maintain a ground track over the imaginary true course that connects the departure point with the destination.

The compass heading is calculated by the pilot before takeoff and may be determined or verified through trial and error by utilizing navigation aids such as a GPS or a Very High Frequency Omni-directional Range (VOR) navigation device, or by observing landmarks from the air. All the pilots in this project planned their compass headings before takeoff, and utilized visual navigation with landmarks. The goal of this section of the research was to test the pilot's ability to maintain a true course line and determine the chance of a pilot's ground track being more than 10 degrees off the planned course. Any errors in planning should be noted and corrected towards the beginning of a flight, so deviations in course throughout the remainder of a flight reflect errors in holding a heading or following the appropriate instrument and navigation checks.

When pilots take practical tests, the examiner is required to hold the pilot candidate to within 10 degrees, plus or minus, of his planned or FAA assigned heading (FAA Commercial Pilot PTS, 1-23). That leaves unanswered the question: What are the chances of a pilot breaking this 10 degree limit?

To answer this question, each flight was examined, and the flight segments in which the aircraft was in cruise, on course climbing, and on course descending were analyzed. Plots were made of the pilot's ground track versus time and ground track deviation frequencies. Standard deviations and percentages were calculated to analyze each pilot's performance.

Another possible measure of a pilot's ground track would be an analysis of how far off his planned course he deviates in terms of feet or miles. This measure was not researched or analyzed in this thesis project.

5.2 Flight 00010

Flight 00010 was flown by two pilots on a practice National Intercollegiate Flying Association (NIFA) navigation run. Table 2.3 provides full flight information. The ground track plot for the flight is contained in Figure 5.1.

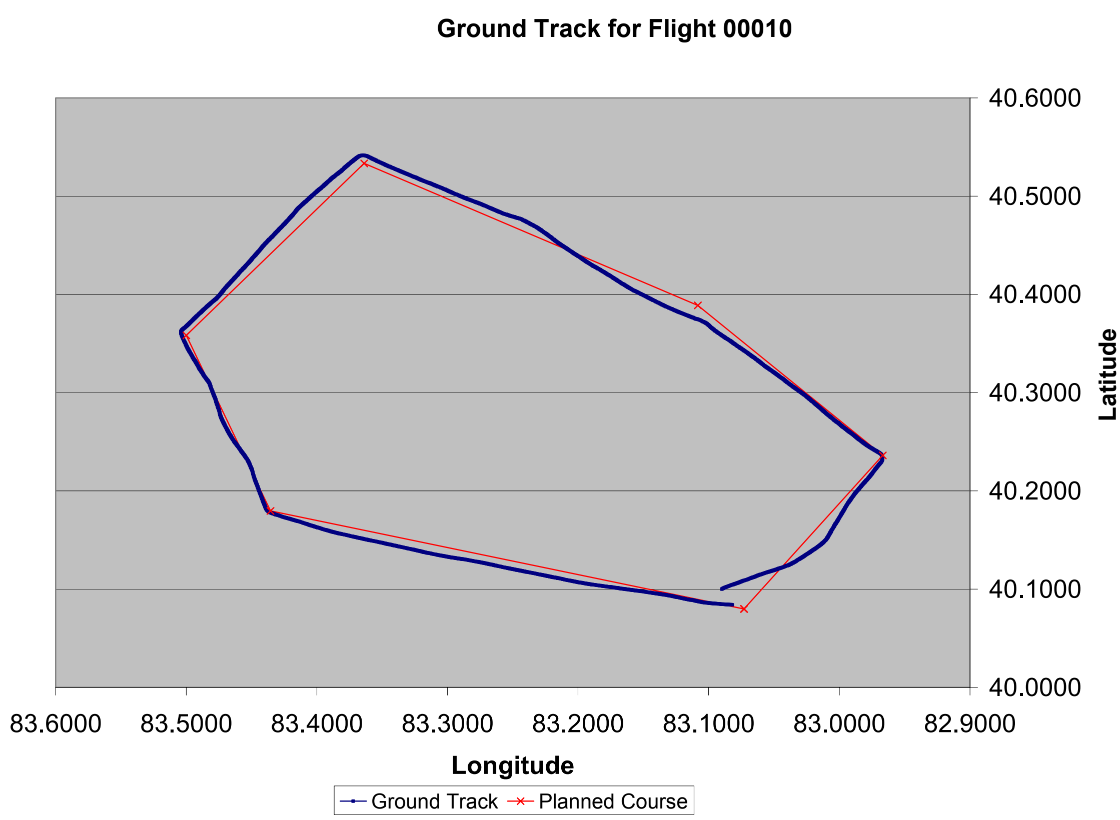


Figure 5.1

Throughout the duration of the flight, the pilot maintained his planned course, with deviations to the right and left. The ground track frequency distribution is approximately normal and is contained in Figure 5.2. The zero line on the y-axis represents the various target ground tracks for the flight.

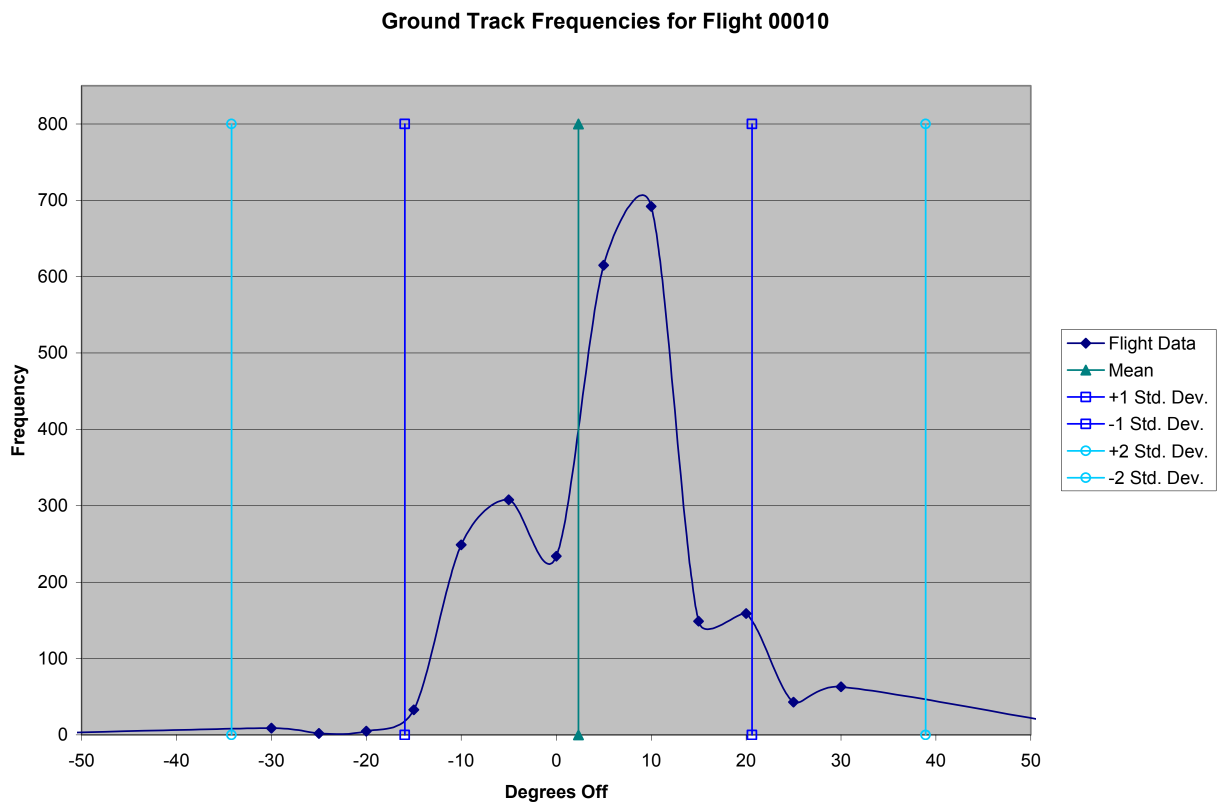


Figure 5.2

From this data, it can be determined that the pilot's average or mean ground track was 2 degrees off the intended course. This means that the pilot was consistently 2 degrees to the right of his target course, which could be a result of incorrect instrument setting, instrument error, change in winds, planning error, or pilot error. It can also be concluded that the pilot was within 10 degrees of his target course 76.73% of the time he was cruising on course.

There seems to be a bi-modal distribution, with the modal lobes centered 7 degrees right and left of course. This probably means that the winds that day were different than forecast, and caused the pilot to track to the right or left of course. There are other possibilities as well, as discussed in the preceding paragraph. If a normal distribution of the data is assumed, despite the bi-modal distribution, a Z value of 0.55 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 58.24% chance that the pilot will exceed the 10 degree limit to the right or left of his target course (Hicks, 312-313).

5.3 Flight 00011

Flight 00011 was flown by the author with another pilot on a practice NIFA navigation run. Table 2.3 provides full flight information. The ground track plot for the flight is contained in Figure 5.3.

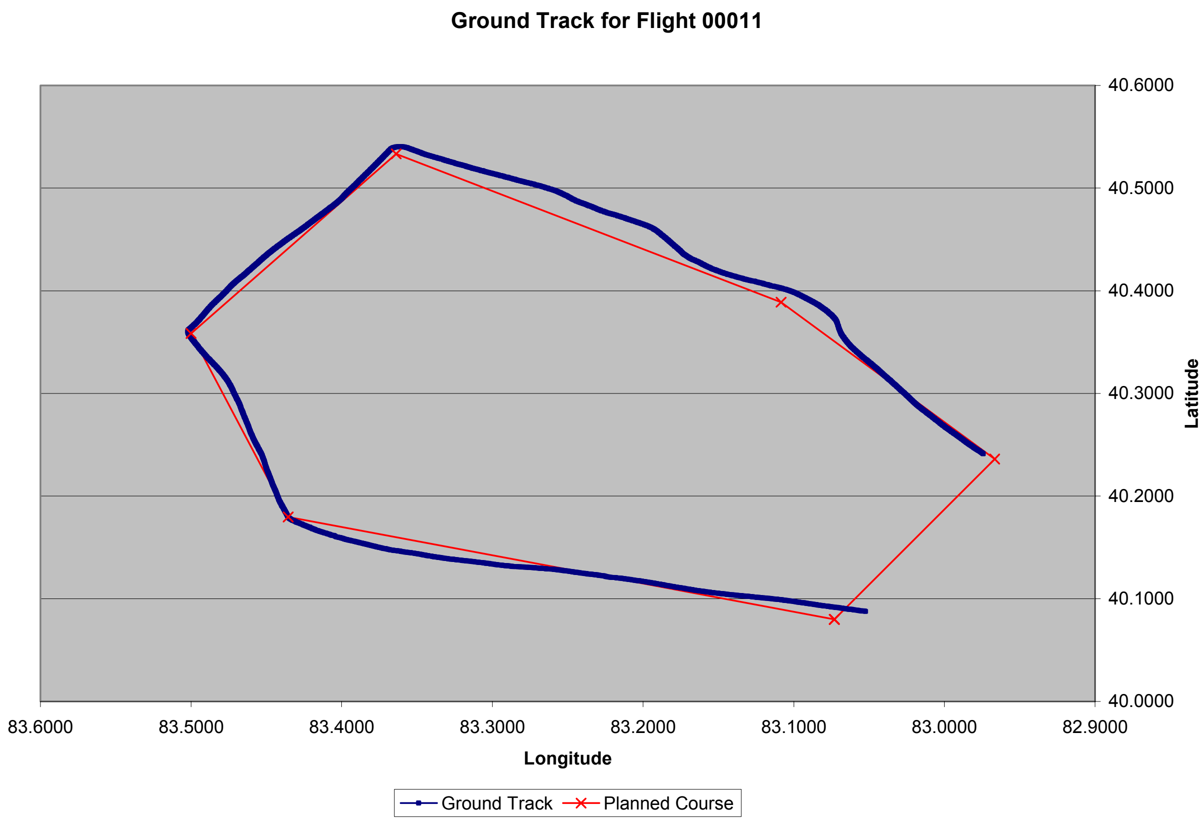


Figure 5.3

Throughout the duration of the flight, the pilot maintained his planned ground track, with deviations to the right and left of his intended course. The ground track frequency distribution is approximately normal and is contained in Figure 5.4. The zero

line on the y-axis represents the various target ground tracks for the flight.

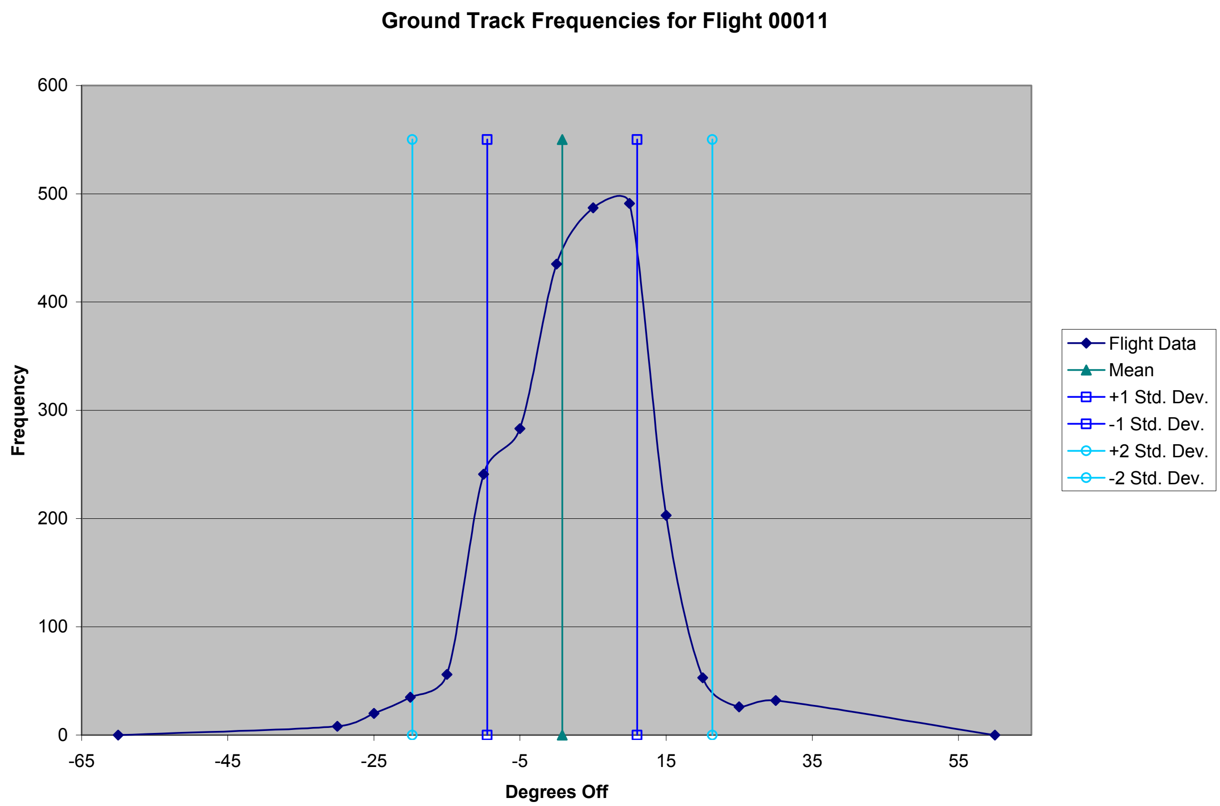


Figure 5.4

From this data, it can be determined that the pilot's average or mean ground track was 1 degree off the intended course. This means that the pilot was consistently 1 degree to the right of his target course, which could be a result of incorrect instrument setting, instrument error, change in winds, planning error, or pilot error. It can also be concluded that the pilot was within 10 degrees of his target course 75.89% of the time he was cruising on course.

If a normal distribution of the data is assumed, a Z value of 0.97 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 33.20% chance that the pilot will exceed the 10 degree limit to the right or left of his target course (Hicks, 312-313).

5.4 Flight 00013

Flight 00013 was flown by a primary student and their CFI on a cross-country training flight from The Ohio State University Airport (KOSU), Columbus, Ohio to Jefferson County Airpark (2G2), Steubenville, Ohio. Table 2.3 provides full flight information. The ground track plot for the flight is contained in Figure 5.5.

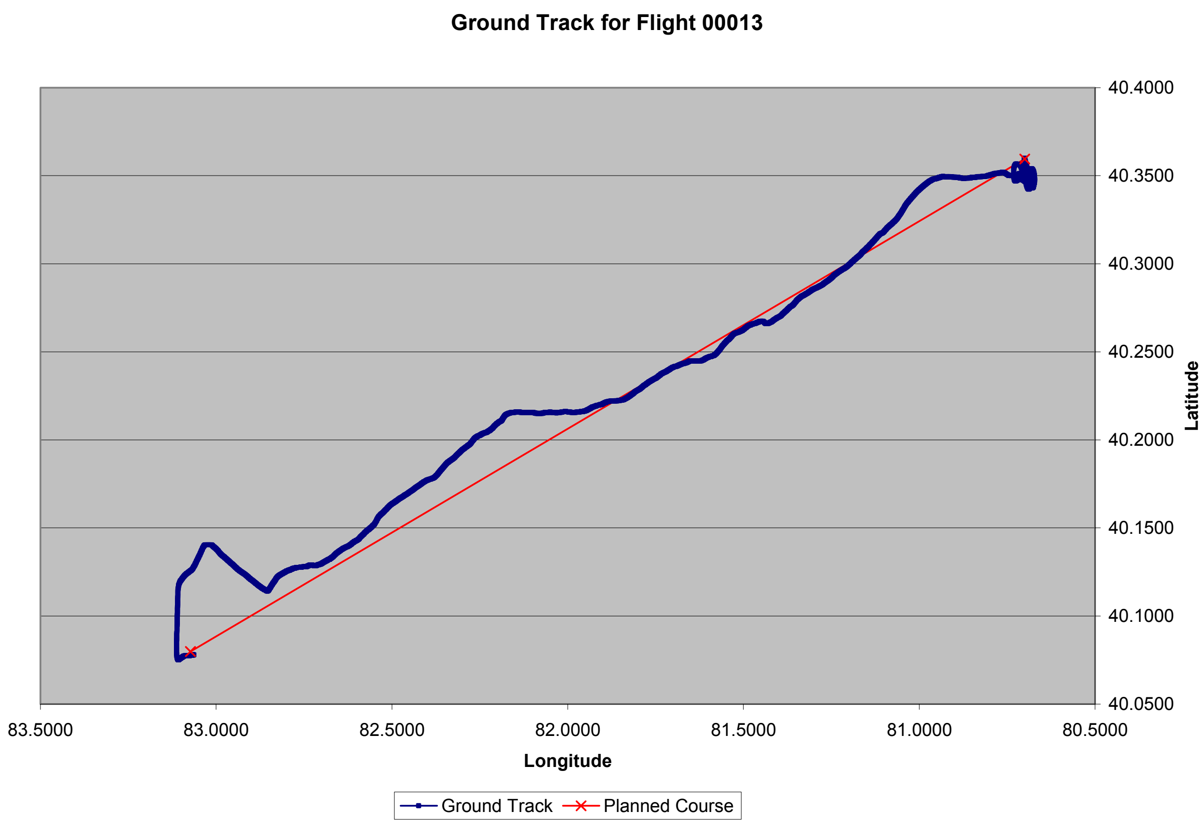


Figure 5.5

Throughout the duration of the flight, the pilot maintained his planned ground track, with deviations to the right and left of his intended course. The ground track frequency distribution is approximately normal and is contained in Figure 5.6. The zero line on the y-axis represents the target ground track for the flight.

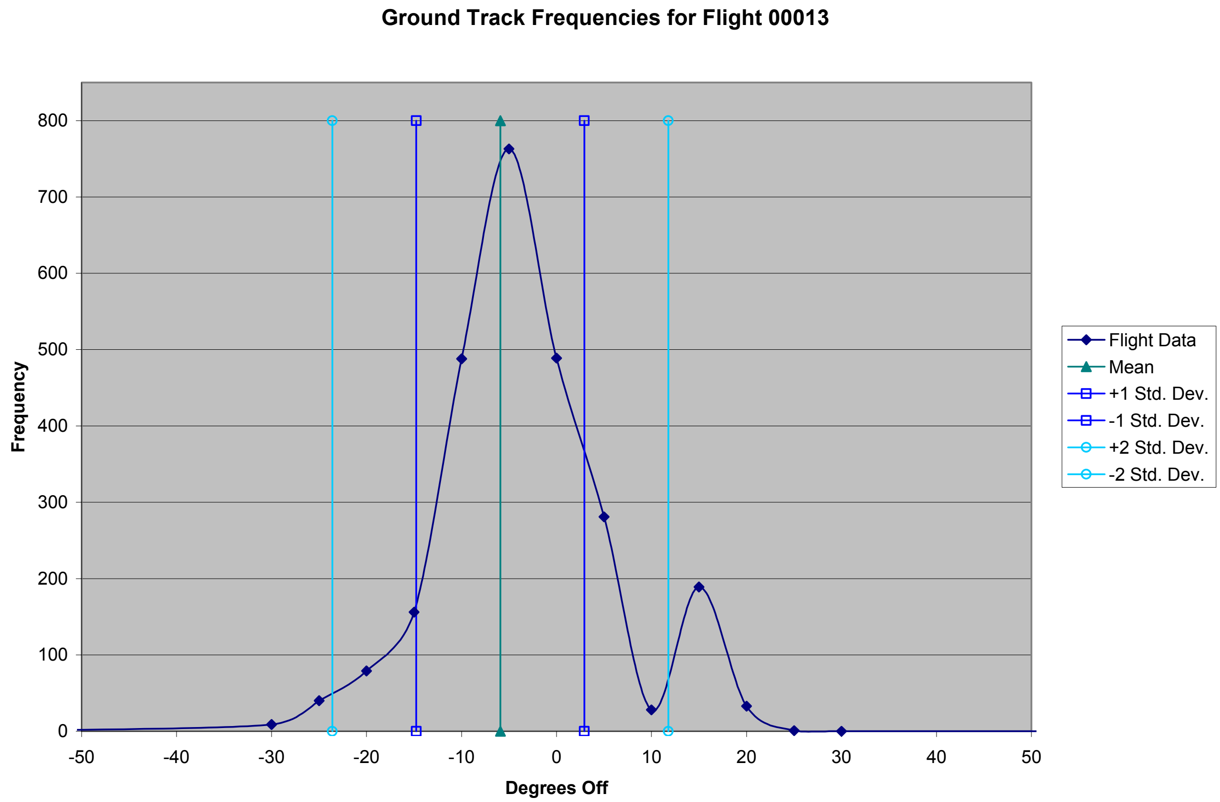


Figure 5.6

From this data, it can be determined that the pilot's average or mean ground track was minus 6 degrees off the intended course. This means that the pilot was consistently 6 degrees to the left of his target course, which could be a result of incorrect instrument setting, instrument error, change in winds, planning error, or pilot error. It can also be concluded that the pilot was within 10 degrees of his target course 92.57% of the time he was cruising on course.

There seems to be a bi-modal distribution, with one modal lobe near the zero line and another centered 15 degrees right of course. This probably means that the pilot flew a heading that allowed for a ground track that was 15 degrees right of course for an extended period. There are other possibilities as well, as discussed in the preceding paragraph. If a normal distribution of the data is assumed, despite the bi-modal distribution, a Z value of 1.13 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 25.84% chance that the pilot will exceed the 10 degree limit to the right or left of his target course (Hicks, 312-313).

5.5 Flight 00015

Flight 00015 was a solo cross-country training flight from The Ohio State University Airport (KOSU), Columbus, Ohio to Mid-Ohio Valley Regional Airport (KPKB), Parkersburg, West Virginia to Highland County Airport (KHOC), Hillsboro, Ohio. Table 2.3 provides full flight information. The ground track plot for the flight is contained in Figure 5.7.

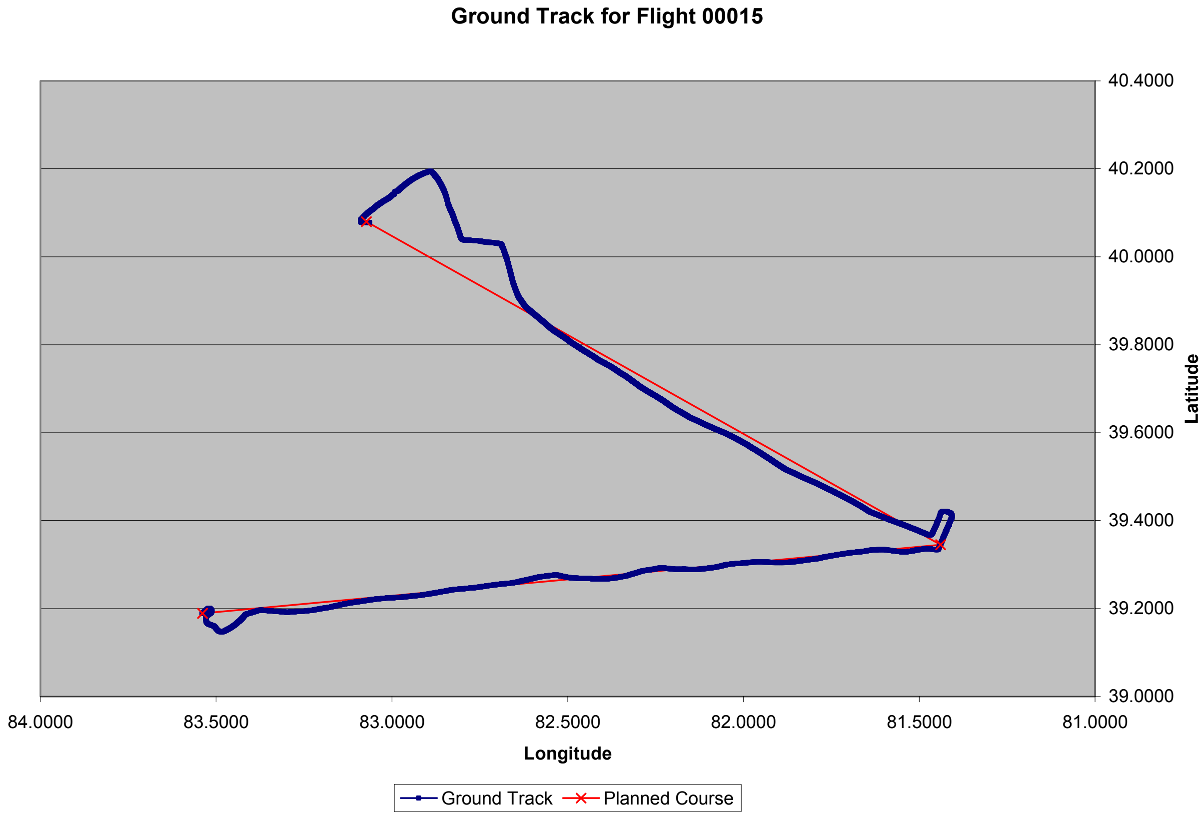


Figure 5.7

Throughout the duration of the flight, the pilot maintained his planned ground track, with deviations to the right and left of his intended course. The ground track frequency distribution is approximately normal and is contained in Figure 5.8. The zero

line on the y-axis represents the various target ground tracks for the flight.

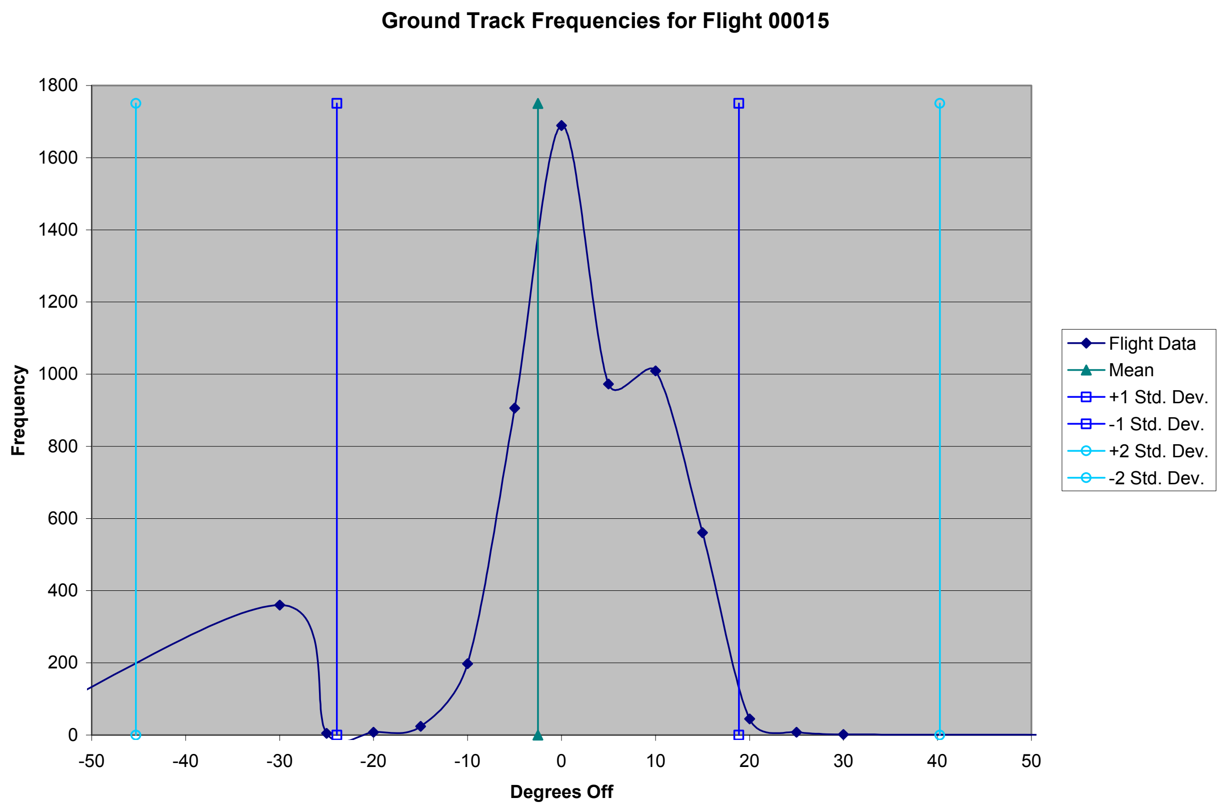


Figure 5.8

From this data, it can be determined that the pilot's average or mean ground track was minus 3 degrees off the intended course. This means that the pilot was consistently 3 degrees to the left of his target course, which could be a result of incorrect instrument setting, instrument error, change in winds, planning error, or pilot error. It can also be concluded that the pilot was within 10 degrees of his target course 82.37% of the time he was cruising on course.

There seems to be a tri-modal distribution, with one modal lobe near the zero line and another centered 10 degrees right of course. There is another modal lobe on the left side of the graph. All of these represent corrections that the pilot made to his course and other errors that were discussed in the preceding paragraph. If a normal distribution of the data is assumed, despite the tri-modal distribution, a Z value of 0.47 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 63.84% chance that the pilot will exceed the 10 degree limit to the right or left of his target course (Hicks, 312-313).

5.6 Flight 00016

Flight 00016 was flown solo by the same pilot that was in command of Flight 00015. This flight was a cross-country training flight from Highland County Airport (KHOC), Hillsboro, Ohio to Bellefontaine Regional Airport (KEDJ), Bellefontaine, Ohio to The Ohio State University Airport (KOSU), Columbus. Table 2.3 provides full flight information. The ground track plot for the flight is contained in Figure 5.9.

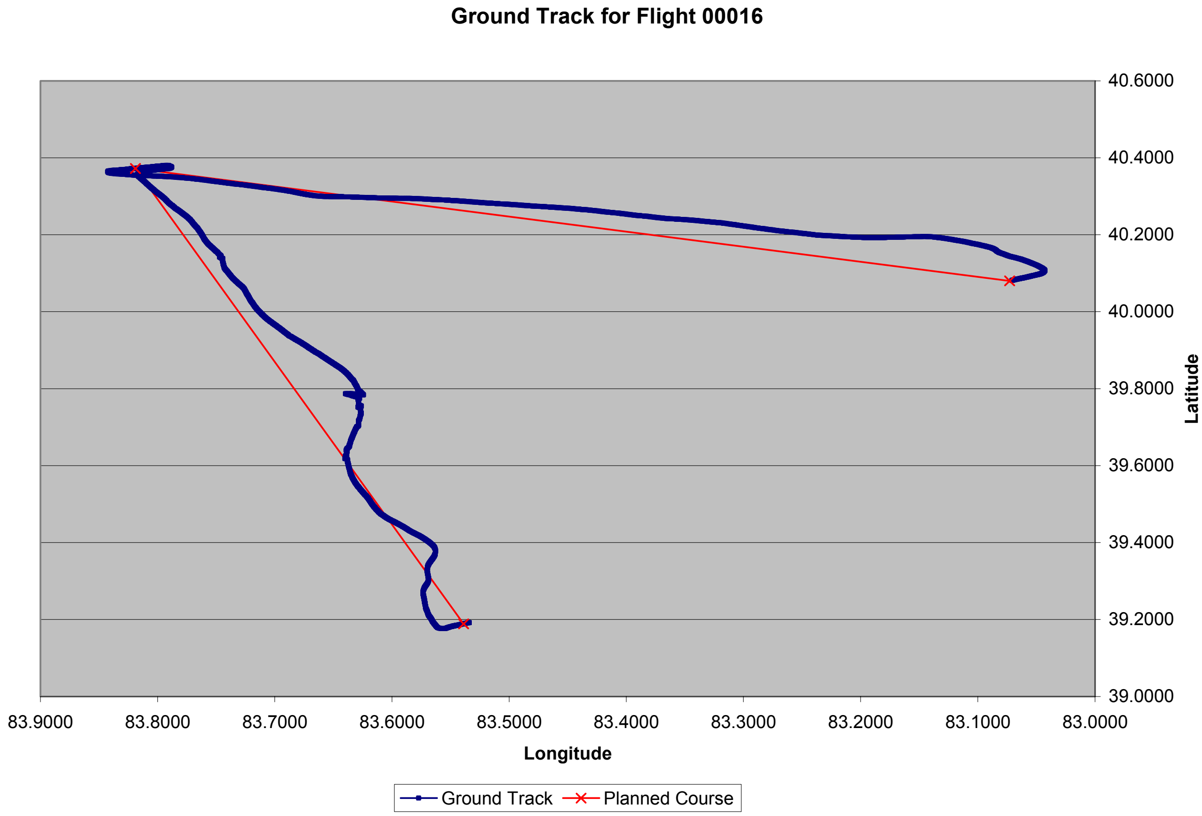


Figure 5.9

Throughout the duration of the flight, the pilot maintained his planned ground track, with deviations to the right and left of his intended course. The ground track frequency distribution is approximately normal and is contained in Figure 5.10. The zero

line on the y-axis represents the various target ground tracks for the flight.

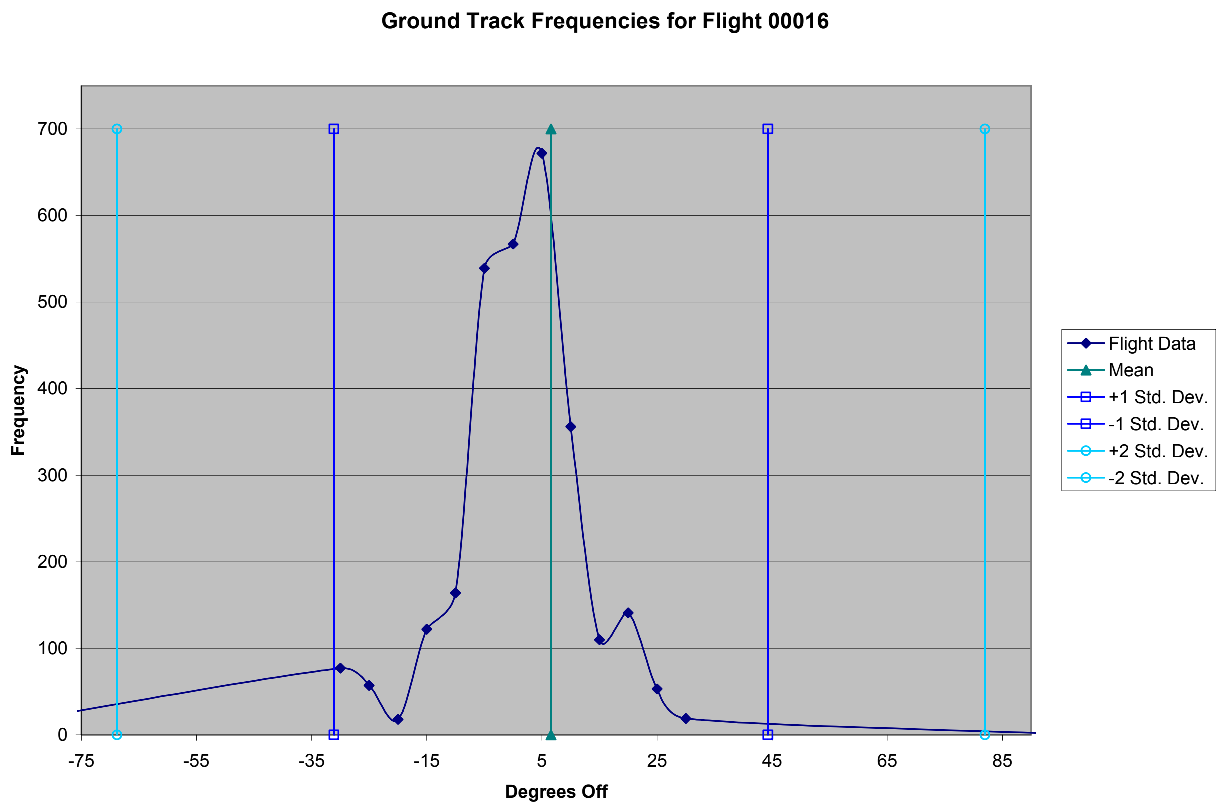


Figure 5.10

From this data, it can be determined that the pilot's average or mean ground track was 7 degrees off the intended course. This means that the pilot was consistently 7 degrees to the right of his target course, which could be a result of incorrect instrument setting, instrument error, change in winds, planning error, or pilot error. It can also be concluded that the pilot was within 10 degrees of his target course 78.72% of the time he was cruising on course.

If a normal distribution of the data is assumed, despite the tri-modal distribution, a Z value of 0.27 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 78.72% chance that the pilot will exceed the 10 degree limit to the right or left of his target course (Hicks, 312-313).

This flight was flown by the same pilot, in the same aircraft, on the same day, in the same state as was Flight 00015. However, there is a huge spread between the data sets. The first flight, 00015, has a lower mean deviation, a higher percentage of being on course, and a lower probability that the pilot will exceed the 10 degree limit. A possibility is that the pilot became fatigued and did not follow his course as well as he had earlier on in the day. Another possibility is that as the day progressed, the winds changed or the atmosphere became less stable and turbulence was encountered.

5.7 Flight 00019

Flight 00019 was flown on a practice National Intercollegiate Flying Association (NIFA) navigation run. Table 2.3 provides full flight information. The ground track plot for the flight is contained in Figure 5.11.

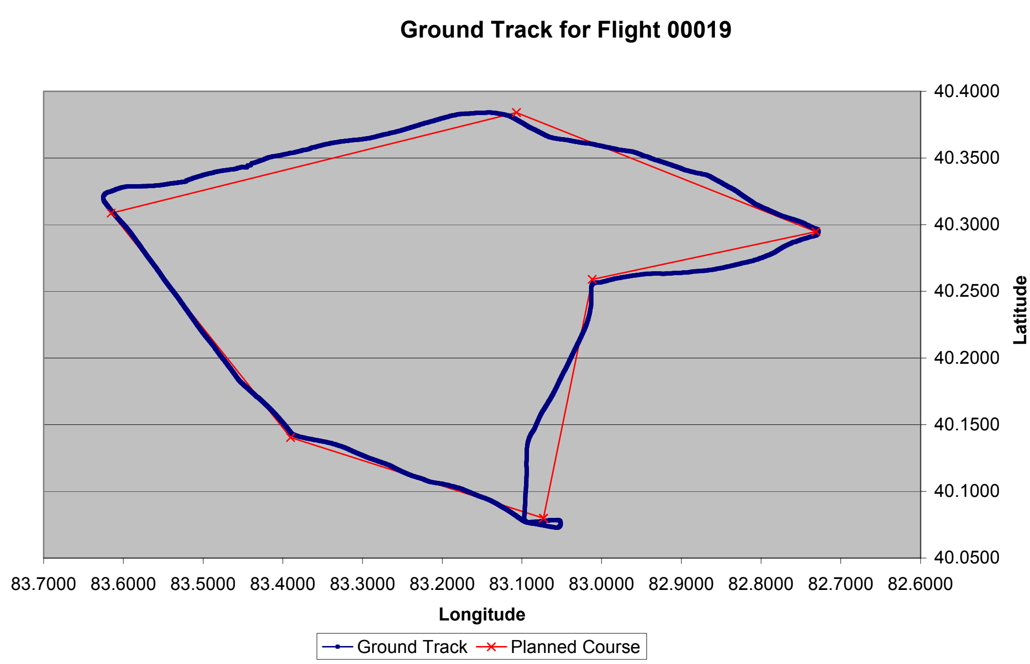


Figure 5.11

Throughout the duration of the flight, the pilot maintained his planned ground track, with deviations to the right and left of his intended course. The ground track frequency distribution is approximately normal and is contained in Figure 5.12. The zero line on the y-axis represents the various target ground tracks for the flight.

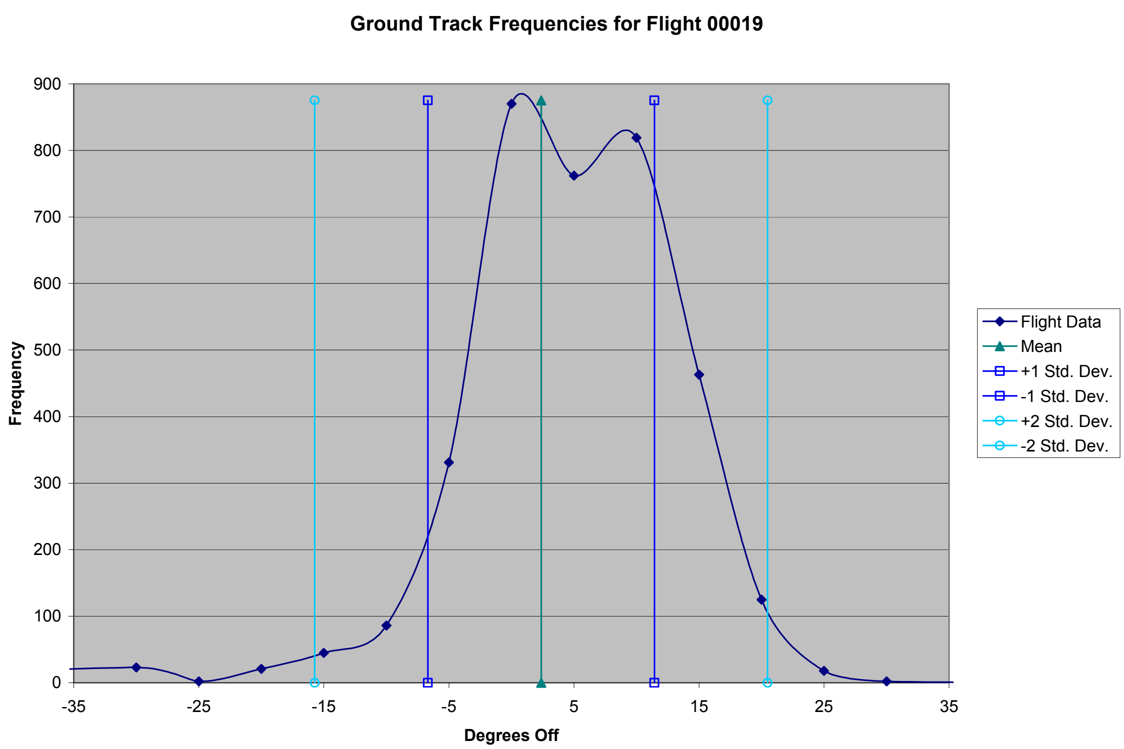


Figure 5.12

From this data, it can be determined that the pilot's average or mean ground track was 2 degrees off the intended course. This means that the pilot was consistently 2 degrees to the right of his target course, which could be a result of incorrect instrument setting, instrument error, change in winds, planning error, or pilot error. It can also be concluded that the pilot was within 10 degrees of his target course 72.86% of the time he was cruising on course.

There seems to be a bi-modal distribution, with the modal lobes centered at 0 degrees right or left of course and 7 degrees right of course. This probably means that the winds that day were different than forecast, and caused the pilot to track to the right of course on one leg. There are other possibilities as well, as discussed in the preceding paragraph. If a normal distribution of the data is assumed, despite the bi-modal distribution, a Z value of 1.10 was calculated. According to the standard Z Value Statistical Table, this leads to the conclusion that there is a 27.14% chance that the pilot will exceed the 10 degree limit to the right or left of his target course (Hicks, 312-313).

5.8 Conclusions

After analyzing the data, which is summarized in Figure 5.13 and Table 5.1, it was found that there are two main components to evaluating a pilot's ability to maintain a ground track.

Flight	Mean Deg Off	Std Dev	w/i 10 (%)	Z Score	Table Look Up	Remain w/i 10 deg (%)	Exceed 10 deg (%)
00010	2	18.28	76.73	0.55	0.7088	41.76	58.24
00011	1	10.27	75.89	0.97	0.8340	66.80	33.20
00013	6	8.84	92.57	1.13	0.8708	74.16	25.84
00015	3	21.38	82.37	0.47	0.6808	36.16	63.84
00016	7	37.7	59.95	0.27	0.6064	21.28	78.72
00019	2	9.05	82.80	1.10	0.8643	72.86	27.14

Table 5.1: Summary of Ground Track Data

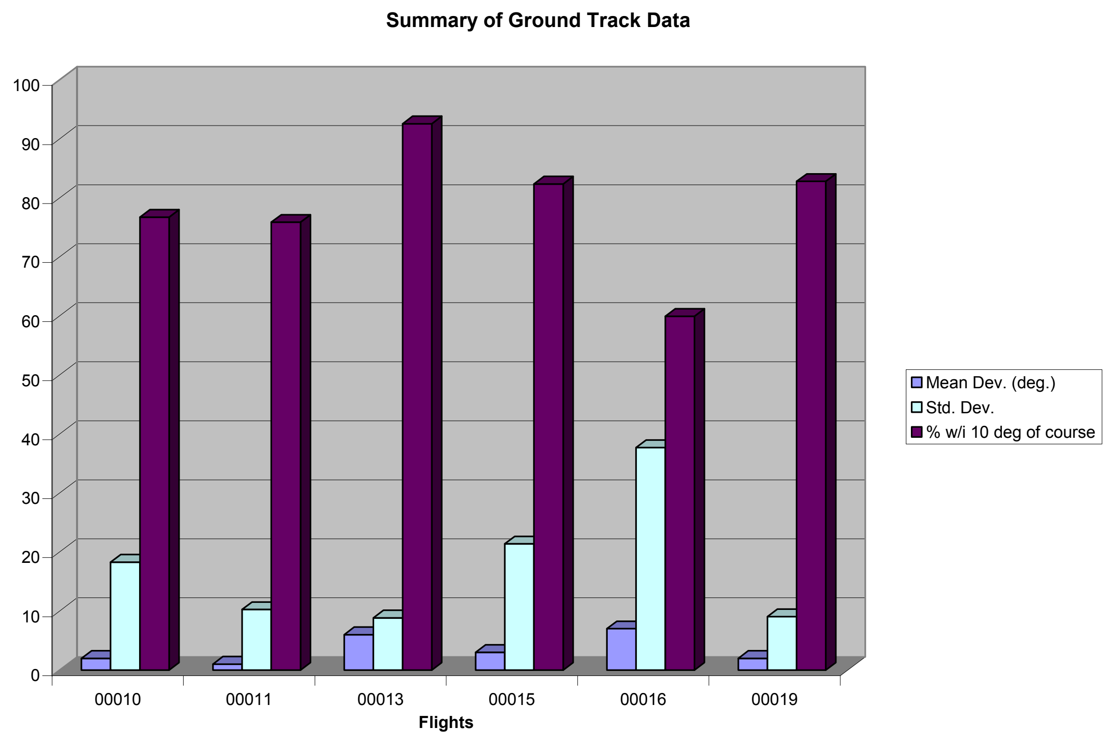


Figure 5.13

One measure is the pilot's actual ability to maintain a ground track, which is based solely off the percentage of a flight where the pilot is within 10 degrees, right or left, of his target course. The other measure is based off the pilot's deviations from the target course, which allows for a Z score to be computed and the chance of a deviation to be determined. The Z Score varies only with standard deviation, in this case, because the 10 degree limit is fixed. While there is a relationship between standard deviation and the chance that the pilot will exceed the 10 degree limit, there seems to be no relationship between a pilot's percentage within 10 degrees of the target course and the pilot's percentage within 10 degrees of course, if all of the data is considered, as in Figure 5.14.

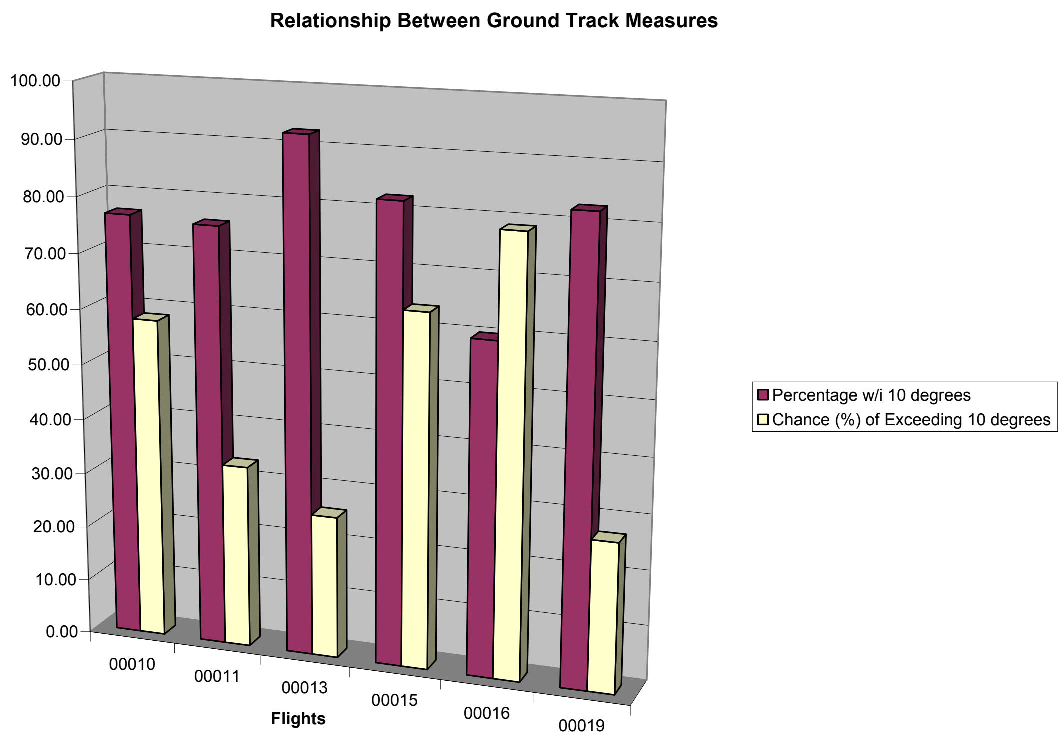

Relationship Between Ground Track Measures
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
00010
00011
00013
00015
00016
00019
Flights
Percentage w/i 10 degrees
Chance (%) of Exceeding 10 degrees

Figure 5.14

CHAPTER 6

CONCLUSIONS AND FURTHER RESEARCH

The use of a FDR to aid in the evaluation of a flight will permit the deviations of a pilot to be recorded and analyzed. Once the empirical data is compiled, the standard deviation of the pilot can be derived. Using simple probability equations from statistics will allow for a prediction of how often a pilot will break the 100 foot window of altitude operation, deviate from course, etc. If the probability is above a determined level, which would have to be set by the FAA, that pilot would have failed to meet the PTS requirements, and more training would be required before that particular pilot would be considered proficient enough to qualify.

In chapter 3, it was shown that the FDR could provide graphic depictions of course and altitude, which can be used to evaluate procedures and actual completion of a flight. In chapter 4, altitude deviations were analyzed. There are two measures of a pilot maintaining an assigned altitude which include the chance of an altitude deviation exceeding 100 feet above or below the target altitude and the percentage of a flight within the same block of altitude. It can be concluded from the data that there is an inverse relationship between these two parameters, but more testing would be required to define the relationship formally. Until that can be done, separate limitations would have to be set up for each measure of maintaining altitude.

In chapter 5, ground tracks were analyzed, and it was found that again the chance of a ground track deviation exceeding 10 degrees to the right or left of the course and the percentage of a flight within the same limits of a course could be used to evaluate the pilot. This data did not support an inverse relationship between the two measures, although more testing would be required to reach a definitive answer. So, in this case, separate limitations would have to be set up for each measure of course tracking performance.

The results of the altitude and ground track analysis were compiled, and no correlations were found between the two. Further research would have to be conducted to further prove that they were independent. However, if a pilot performed especially well maintaining altitude or ground track, but was deficient at the other, it could be determined that the pilot was fixating on one parameter in flight, and was not properly multi-tasking. This insight could help an instructor diagnose a common problem encountered while training new pilots.

The evaluation of many complex flight maneuvers, various instruction techniques, and the evaluation of complete flights was beyond the scope of this project. However, all flight maneuvers are a modification of straight and level flight, and therefore the groundwork has been laid for future research in this area. The analysis of takeoffs, landings, turns, climbs, descents, and other training or aerobatic maneuvers will need to be evaluated. In addition to percentages, chances of deviation, and standard deviations, other parameters can be examined such as dampening ratios, consistency, and coordination, to name just a few. After all of the research is completed, the FAA can set forth new PTS requirements and be able to evaluate pilots more objectively.

In the meantime, the results of this project can be put to immediate use. A FDR can be used to create a picture of a solo flight for an instructor. The flight instructor can evaluate if the student arrived at the correct airport, entered the traffic pattern properly, and landed the aircraft. The instructor can look at the cruise portions of the flight and determine if the student maintained altitude and how severe the deviations were. The instructor can see if the student navigated properly, maintaining the planned course.

If the data sets are kept, these records of student performance can also be used to evaluate instructor performance. If one particular instructor's students are mostly deficient in a certain skill area, such as maintaining altitude, the instructor will be able to conclude that he or she is not teaching that concept properly. In addition, flights will be able to be recreated graphically in real time, allowing the instructor to review the details of a flight or a maneuver while on the ground. Research could also be done in this field, to discover whether the use of FDRs could possibly speed up or lower the cost of student pilot training, much like flight training devices and flight simulators do. Using the data from the FDR, flights could even be recreated in a flight training device or simulator.

To successfully allow the flight instructors at The Ohio State University, or any other flight school, to use the findings of this thesis, a little further work would be very beneficial. A simple software program would have to be written that would automatically create the appropriate files and plots when the raw GPS file is downloaded. This would make solo flight evaluations simple and efficient, and save the instructor from having to learn to use all the various software packages and spreadsheets that were used in this project.

In addition to helping with instruction and evaluation of pilots, the use of an FDR in aircraft can be beneficial in other ways. If a telemetry device could be attached, a ground station could track aircraft heading, groundspeed, and altitude without radar. In the case of an aircraft accident or incident, the data could be downloaded and analyzed. The use of a small FDR has many implications, and can completely revolutionize the aviation industry. From flight instruction, to collision avoidance, to accident investigation, to pilot testing and evaluation, the FDR is a powerful tool that can be used to a pilot's advantage.

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